Chapter 12: Cross sectoral perspectives

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Executive summary

A synthesis of costs and potentials of mitigation actions across sectors is provided, based on the findings from the other chapters, for both 2030 and 2050. A comparison is also presented on the findings of bottom-up models and top-down models or Integrated Assessment Models (IAMs), see Figure 12.2, with a discussion presented on similarities and differences between the two approaches. {12.2}

The total emission reduction potential achievable by the year 2030, calculated based on sectoral assessments, is sufficient to reduce global greenhouse gas emissions to half of the current (2018) level. The total potential is achieved by implementation of a wide range of different mitigation options, see Table 12.3. Low-cost options (with mitigation costs lower than USD 20 tCO_2) make up more than half of this potential and such options are widely available for all sectors, except industry (*medium evidence, high agreement*). {12.2}

Carbon Dioxide Removal (CDR) is an essential element in most scenarios that limit warming to 1.5°C–2°C by 2100 (*robust evidence, high agreement*). Any target that implies net zero GHG emissions will imply some degree of CDR to offset residual emissions. CDR is also needed to return from temporary overshoots of carbon budgets or temperature thresholds by delivering net negative emissions (*robust evidence, high agreement*). All Illustrative Pathways (IPs) use either land-based CDR in the form of afforestation /reforestation or technological CDR (BECCS, DACCS, EW), or both, in meeting low-temperature targets of 1.5°C–2.0°C (*high confidence*). As a median value [interquartile range] across the scenarios examined, required cumulative CDR reaches 551 [375-734] $GtCO_2$ over the 21st century (2016–2100), with annual volumes at 3.2 [1.8–4.5] $GtCO_2\ yr^{-1}$ for BECCS/DACCS/EW and 2.2[1.0-4.9] $GtCO_2\ yr^{-1}$ for net AFOLU in 2050 for 1.5°C–2°C scenarios (scenario categories C1-C3). {12.3, 12.7}

Direct air capture and carbon storage (DACCS), enhanced weathering (EW)and ocean-based approaches (including ocean alkalinity management and ocean fertilisation) have moderate to large mitigation potential. The potential for DACCS is limited mainly by requirements for low-carbon energy and by cost ([60–500] USD tCO_2^{-1}; *medium evidence, medium agreement*). Enhanced weathering has the potential to remove [<1 to ~100] $GtCO_2\ yr^{-1}$, at costs ranging from [24–578] USD tCO_2^{-1} (*medium evidence, medium agreement*). Ocean-based approaches have the potential to remove [1–100] $GtCO_2\ yr^{-1}$ at costs of [40 to 500] USD tCO_2^{-1} (*medium evidence, medium agreement*). There is uncertainty about the extent of their future deployment. {12.3}

Food systems currently contribute some [32-36%] to global greenhouse gas (GHG) emissions, while there is still wide-spread food insecurity and malnutrition. Absolute GHG emissions from food system increased since 1990 from 16 to 18 $GtCO_2$-eq yr^{-1}. Both supply and demand side measures can contribute to mitigation and realising the full mitigation potential requires commitment from all actors in the food system *(robust evidence, high agreement*). {12.4}

Diets high in plant protein and low in meat and dairy are associated with lower GHG emission intensities. Red meat shows the highest GHG intensity. Studies show that in regions with excess consumption of calories and animal-source food, a shift to diets with higher share of plant protein could lead to substantial reduction of both GHG emissions and nutrient losses as compared to current dietary patterns, while at the same time providing health benefits and reducing mortality from diet-related non-communicable diseases *(robust evidence, high agreement*). {12.4}

Emerging food technologies such as cellular agriculture or controlled environment agriculture promise substantial reduction in direct GHG emissions from food production. However, the full mitigation potential of such technologies can only be realised with low GHG energy systems *(limited evidence, high agreement).* {12.4}

Pathways that limit warming to 1.5°C require extensive land-based mitigation, with most including Afforestation/Reforestation (A/R), bioenergy, and in most cases, bioenergy combined with carbon capture and storage (BECCS). At the same time, climate change creates additional stresses on land, exacerbating existing risks to livelihoods, biodiversity, human and ecosystem health, infrastructure, and food systems (*robust evidence*, *high agreement*). {12.5}

Many mitigation options require land, although not all of those are considered land based. The mitigation value differs between the options and is context specific. All options can result in positive effects on sustainability or in negative effects, depending on the criteria chosen, as well as the local context, management regime, prior land use, and scale. Careful integration of appropriate mitigation options with existing land uses helps to mitigate trade-offs and can contribute to adaptation and combatting desertification and land degradation, enhance food security, and improve resilience through maintenance of the productivity of the land resource base (*robust evidence, high agreement*). {12.5}

Mitigation measures are commonly categorised by the sector in which they are applied, with some measures being applied in more than one sector. Examples of mitigation measures used in more than one sector include renewable energy technologies, carbon capture, utilisation and storage (CCUS) and fuel cells. Further areas where mitigation is considered from a cross-sectoral perspective are where demand and production for energy, goods and services in one sector will impact on the level of activity and hence emissions intensity of another, and where there is competition for resources such as land, biomass and minerals *(robust evidence, high agreement)*. {12.6.1}

Synergies and trade-offs resulting from mitigation policies are often not discernible from either the sector-specific context nor the integrated global and regional context but rather require a cross-sectoral integrated or multiple-objective-multiple-impact policy framework. Strong inter-dependencies and cross-sectoral linkages create both opportunities for synergies and the need to address trade-offs related to mitigation options and technologies. This can only be done if coordinated sectoral approaches to climate change mitigations policies that mainstream these interactions are adopted *(robust evidence, high agreement).* Integrated planning and cross-sectoral alignment of climate change policies are particularly evident in developing countries' NDCs pledged under the Paris Agreement, where key priority sectors such as agriculture and energy are closely aligned between the proposed mitigation and adaptation actions in the context of sustainable development and the SDGs. Example is the integration between smart agriculture and low carbon energy *(robust evidence, high agreement).* {12.6.2}

Carbon leakage (see Chapters 3 and 13 for concept and definition) is a critical cross-sectoral and cross-country outcome of differentiated climate policy. Three types of cross-sectoral spill-overs related to leakage are identified: 1) domestic cross-sectoral spill-overs within the same country; 2) international spill-overs within a single sector resulting from substitution of domestic production of carbon-intensive goods with their imports from abroad; and 3) international cross-sectoral spill-overs among sectors in different countries *(robust evidence, high agreement).* Concerning the magnitude of carbon leakages and related industry competitiveness effects, there are no significant differences in the reported results compared to those reported in AR5. Nevertheless, an important development since AR5 is the emergence of research on carbon leakage related to global value chains and international transport. Research on leakage related to basic materials, for example, indicate that for developing countries the positive effect on carbon leakage from the expansion of economic activity dominates the negative effect on carbon leakage from technological spill-overs, while the reverse is the case for developed countries. The literature estimates that international transport is responsible for about a third of worldwide trade-related emissions, and over 75% of emissions for major manufacturing categories. Carbon leakage would potentially increase the emissions from transportation significantly as the trade of major consuming economies in the EU and US would shift towards distant trading partners in East and South Asia *(robust evidence, medium agreement).* {12.6.3}

Cross-sectoral considerations in mitigation finance are critical for the effectiveness of mitigation action as well as for balancing the often conflicting social, developmental, and environmental policy goals at the sectoral level. True resource mobilisation plans that properly address mitigation costs and benefits at sectoral level cannot be developed in isolation of their cross-sectoral implications *(medium evidence, high agreement).* Mitigation finance by Multilateral Development Banks (MDBs) has mostly focused on sectoral solutions and has not been able to properly leverage cross-sectoral synergies. There is an urgent need for multilateral financing institutions to align their frameworks and delivery mechanisms to facilitate cross-sectoral solutions as opposed to causing competition for resources among sectors *(medium evidence, medium agreement).* Private development financing through public-private partnership (PPP) and other related variants of blended financing are a growing source of mitigation finance leveraging cross-sectoral synergies and managing trade-offs *(limited evidence, high agreement).* {12.6.4}

Understanding co-benefits and trade-offs associated with sectoral mitigation policies is important for the proper design of sectoral and cross-sectoral mitigation policies and their implementation (*medium evidence, medium agreement*). Co-benefits and trade-offs could result directly from mitigation action in a given sector or indirectly from the mitigation actions in other sectors enabled by the mitigation action in the given sector. The UN Sustainable Development Goals (SDGs) are increasingly being used to provide a common framing of the wider impacts of mitigation actions and options in the different sector. CDR options can have positive impacts on ecosystem services and the SDGs, but also potential adverse side effects. Transforming food systems has potential co-benefits for several SDGs, but also trade-offs. Land based mitigation measures may have multiple co-benefits but may also be associated with trade-offs among environmental, social and economic objectives. The possible implementation of different mitigation options thus depends on how societies prioritise mitigation versus other products and services obtained from land, versus nature conservation and soil/water/biodiversity protection. Other considerations include society’s future dependence on carbon-based energy and materials, requirement for negative emissions, and whether these needs can be met in alternative ways. {12.3, 12.4, 12.5, 12.6.1, 12.7}

Polycentric governance of carbon dioxide removal, food systems and land-based mitigation can support effective and equitable policy implementation (*medium evidence, high agreement*). Effectively responding to climate change while advancing sustainable development will require coordinated efforts among a diverse set of state- and non-state-actors on global, national and sub-national levels. Beyond the common task of establishing reliable systems for measurement, reporting and verification that allow evaluation of mitigation outcomes and co-benefits, governance arrangements in public policy domains that cut through traditional sectors are confronted with specific challenges. CDR can draw on widespread experience with governing conventional mitigation but needs to overcome significant challenges regarding political acceptance to allow full climate policy integration. Food systems governance may be pioneered through local food policy initiatives, but governance on the national level tends to be fragmented, and thus have limited capacity to address structural issues like inequities in access. The governance of land-based mitigation can draw on learning from previous experience with regulating biofuels and forest carbon; however, integrating this learning requires governance that goes beyond project-level approaches. {12.7}

12.1 Introduction

12.1.1 Chapter overview

The scope of this chapter follows closely the terms of reference specified for the chapter in the approved scope outline for WGIII contribution to AR6. The approved outline emphasises two broad domains to be covered by the assessment in the chapter, namely, a cross-sectoral perspective on mitigation potentials and related synergies and trade-offs, and assessment of food systems, large-scale land-based mitigation and CDR technologies. Accordingly, the chapter is structured around these two domains with a number of sections synthesising and summarising cross-sectoral aspects of mitigation including potentials, technologies, synergies, and trade-offs while the other sections providing assessment of GHG aspects, as well as impacts, risks and opportunities, related to CDR technologies, large scale land-based mitigation, and mitigation options related to food systems.

Figure 12.1 presents a schematic of sectoral dimensions and cross-sectoral perspectives addressed in Chapter 12, which brings together cross-sectoral perspectives on mitigation options in the context of sustainable development, sectoral policy interactions, governance, implications in terms of international trade, spill-over effects, and competitiveness, and cross-sectoral financing options for mitigation. While cross-sector technologies as such are covered in more detail in sectoral chapters, this chapter covers important cross-sectoral linkages and provides synthesis conclusions concerning costs and potentials of mitigation options, and co-benefits and trade-offs that can be associated with deployment of mitigation options. Additionally, Chapter 12 covers CDR options and specific considerations related to land use and food systems, complementing Chapter 7. The literature assessed in the chapter includes both peer-reviewed and grey literature post IPCC-AR5 including IPCC-SR1.5, IPCC-SRCCL, and the more recent publications. Knowledge gaps are identified and reflected where encountered, and to ensure consistency a strong link is maintained with sectoral chapters and the relevant global chapters of the report.

12.1.2 Chapter content

Chapters 5 to 11 present the mitigation measures that are applicable in individual sectors, and potential co-benefits and adverse side effects of these individual measures. Chapter 12 brings together the cross-sectoral aspects of these assessments including synergies and trade-offs as well as the implications of measures that have application in more than one sector and measures where implementation in one sector impacts implementation in other sectors.

Taking stock of the sectoral mitigation assessments, Chapter 12 provides a summary synthesis of sectoral mitigation costs and potentials in the short and long term along with comparison to the top-down IAM assessment literature.

In the context of cross-sectoral synergies and trade-offs, the chapter identifies a number of mitigation measures that have application in more than one sector. Renewable energy technologies such as solar and wind may be used for grid electricity supply, as embedded generation in the buildings sector and for energy supply in the agriculture sector. Hydrogen and fuel cells, coupled with renewable energy technologies for producing the hydrogen, is being explored in transport, urban heat, and industry and for balancing electricity supply. Electric vehicles are considered an option for balancing variable power. Carbon Capture and Storage (CCS) has potential application in a number of industrial processes (cement, iron and steel, petroleum refining and pulp and paper) and the fossil fuel electricity sector, and when coupled with energy recovery from biomass (BECCS), CCS can provide CDR. On the demand side, energy efficiency options find application across the sectors, as does reducing demand for goods and services, and improving material use efficiency. Deep dives into these areas of cross-sectoral perspectives are provided for CDR, food systems, and land-based mitigation options.

A range of examples of where mitigation measures result in cross-sectoral interactions and integration is identified. The mitigation potential of electric vehicles, including plug-in hybrid hybrids, is linked to the extent of decarbonisation of the electricity grid, as well as to the liquid fuel supply emissions profile. Making buildings energy positive, where excess energy is used to charge vehicles, can increase the potential of electric and hybrid vehicles. Advanced process control and process optimisation in industry can reduce energy demand and material inputs, which in turn can reduce emissions linked to resource extraction and manufacturing. Trees and green roofs planted to counter urban heat islands reduce the demand for energy for air conditioning and simultaneously sequester carbon. Material and product circularity contributes to mitigation, such as treatment of organic waste to reduce methane emissions, generate renewable energy, and to substitute for synthetic fertilisers.

The chapter also discusses cross-sectoral mitigation potential related to diffusion of General Purpose Technologies (GPT), such as electrification, digitalisation, and hydrogen. Examples include the use of hydrogen as an energy carrier, which, when coupled with renewable energy, has potential for driving mitigation in energy, industry, transport, and buildings (Box 12.4), and the potential of digitalisation for reducing GHG emissions through energy savings across multiple sectors.

The efficient realisation of the above examples of cross-sectoral mitigation would require careful design of government interventions across planning, policy, finance, governance, and capacity building dimensions. In this respect, Chapter 12 assesses literature on cross-sectoral integrated policies, cross-sectoral financing solutions, cross-sectoral spill-overs and competitiveness effects, and on cross-sectoral governance for climate change mitigation.

Finally, in the context of cross-sectoral synergies and trade-offs, the chapter assesses the non-climate mitigation co-benefits and adverse effects in relation to SDGs, building on the fast-growing literature on the non-climate impacts of mitigation.

12.1.3 Chapter Layout

The chapter is mapped into seven sections. Cost and potentials of mitigation technologies are discussed in Section 12.2, where a comparative assessment and a summary of sectoral mitigation cost and potentials is provided in coordination with the sectoral Chapters 5-11, along with a comparison to aggregate cost and potentials based on IAMs of Chapter 3.

Section 12.3 provides a synthesis on the state and potential contribution of CDR technologies to climate change mitigation. CDR options associated with the AFOLU and Energy sector are dealt with in Chapter 6 and Chapter 7 and synthesised in Section 12.3. Others, not dealt with elsewhere, are covered in more detail. A comparative assessment is provided for the different CDR options in terms of costs, potentials, impacts and risks, and synergies and trade-offs.

Section 12.4 assesses the literature on food systems and GHG emissions. The term ‘food system’ refers to a composite of elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes. Climate Change mitigation opportunities and related implications for sustainable development and adaptation are assessed, including those arising from food production, landscaping, supply chain and distribution, and diet shifts.

Section 12.5 assesses impacts, risks and opportunities associated with land-based mitigation options, other than those that are inherent in the food system. The assessment also covers mitigation options that are commonly not designated land-based, but may still be associated with land occupation and consequent impacts, risks and opportunities. The section builds on the recent IPCC-SRCCL and considers implications for food security, land and water resources biodiversity, and ecosystem services.

Section 12.6 provides a cross-sectoral perspective on mitigation, co-benefits, and trade-offs, including those related to sustainable development and adaptation. The synthesised sectoral mitigation synergies and trade-offs are mapped into options/technologies, policies, international trade, and finance domains. Cross-sectoral mitigation technologies fall into three categories in which the implementation of the technology: (i) occurs in parallel in more than one sector; (ii) could involve interaction between sectors, and/or (iii) could create resource competition among sectors. Policies that have direct sectoral effects include specific policies for reducing GHG emissions and non-climate policies that yield GHG emissions reductions as co-benefits. Policies may also have indirect cross-sectoral effects, including synergies and trade-offs that may, in addition, spill over to other countries.

The last section (Section 12.7) addresses governance across the various means, technologies and options for implementations of mitigation efforts at the sectoral and cross-sectoral levels and in relation to sustainable development and other societal goals. Specific emphasis is devoted to governance related to CDR, food systems, and land-based mitigation.

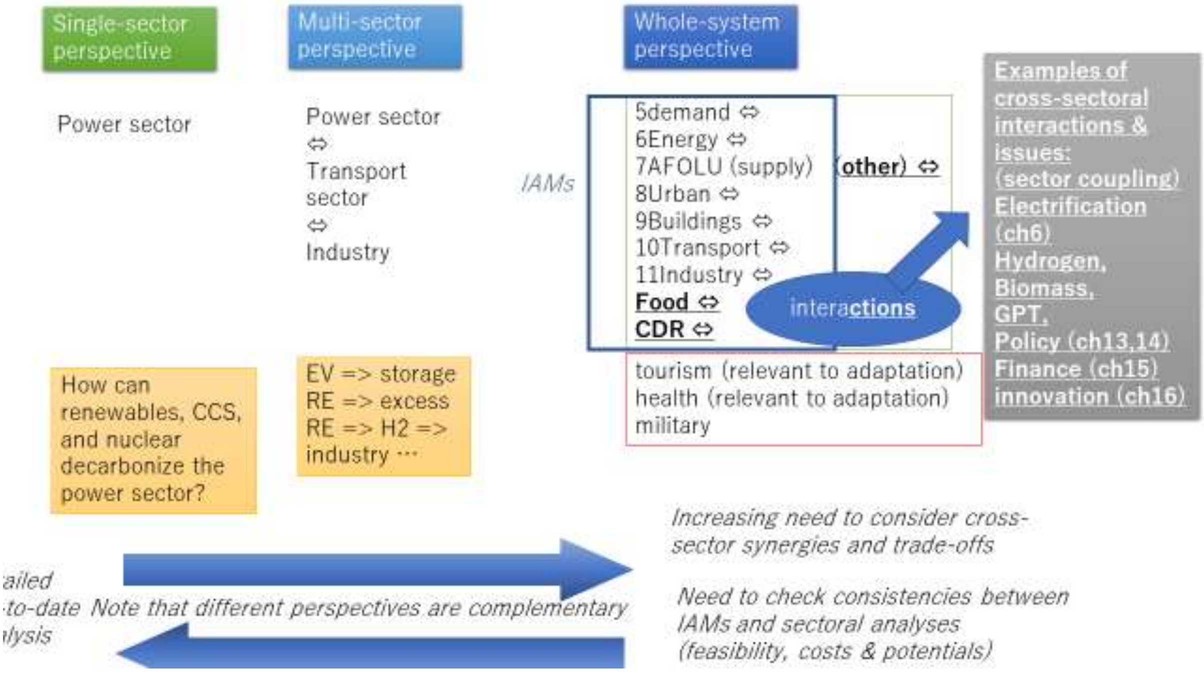


Figure 12.1 A schematic of cross-sector perspectives addressed in Chapter 12

12.2 Aggregation of sectoral costs and potentials

The aim of this section is to provide a consolidated overview of the net emissions reduction potentials and costs for mitigation options available in the various sectors dealt with in Chapters 5 – 11 of this assessment report. The granular overview provides policy makers with an understanding of which options are more or less important in the short term, and which ones are more or less costly. The intention is not to provide a high level of precision for each technology, but rather to indicate relative importance on a global scale and whether costs are low, intermediate or high. The section starts with an introduction (12.2.1), providing definitions and the background. Next, net emission reduction potentials and the associated costs for the year 2030 are presented and compared to earlier estimates (12.2.2) and with the outcomes of Integrated Assessment Models (12.2.3). Finally, an outlook to the year 2050 is provided (12.2.4).

12.2.1 Introduction

The term 'mitigation potential' is used here to report the quantity of net greenhouse gas emissions reductions that can be achieved by a given mitigation option relative to specified emission baselines. Net greenhouse gas emission reductions is the sum of reduced emissions and/or enhanced sinks. Several types of potential can be distinguished. The technical potential is the mitigation potential constrained by theoretical limits as well as availability of technology and practices. Quantification of technical potentials take into account primarily technical considerations, but social, economic and/or environmental considerations are occasionally also considered, if these represent strong barriers for the deployment of an option. Finally, the economic potential, being the potential reported in this section, is the portion of the technical potential for which the social benefits exceed the social costs, taking into account a social discount rate and the value of externalities (all these definitions are as presented in the Glossary of this assessment report). In this section, only externalities related to greenhouse gas emissions are taken into account. They are represented by using different cost cut-off levels of options in terms of USD per tonne of avoided CO_2-eq emissions.

The analysis presented here is based, as far as possible, on Chapters 6–7 and 9–11, which have assessed costs and potentials for each individual sector, here referred to as 'sectoral potentials'. In the past, these were designated bottom-up potentials, in contrast to the top-down potentials that are obtained from integrated energy-economic models and integrated assessment models (IAMs). However, IAMs increasingly include 'bottom-up' elements, which makes the distinction less relevant. Still, sectoral studies often have more technical and economic detail than IAMs. They may also provide more up-to-date information on technology options and associated costs. However, aggregation of results is more complex, and although interactions and overlap are corrected for as far as possible in this analysis, it is recognised that such systemic effects are more rigorously taken into account in IAMs. A comparison is made between the sectoral results and the outcomes of the IAMs in Section 12.2.3.

Costs of options will change over time. For many technologies, costs will come down as a result of technological learning. An attempt has been made to take into account the average, implementation-weighted costs until 2030. However, the underlying literature did not always allow such costs to be presented. The latest GWP values were used where possible; however, the underlying literature did not always allow for this to be done. For the year 2030, the results are presented similarly to AR4, with a breakdown of the potential in cost bins. For the year 2050, a more qualitative approach is provided.

As indicated previously, net emission reduction potentials are presented based on comparison with a baseline scenario. Unfortunately, not all costs and potentials found in the literature are determined against the same baseline. Typical baseline scenarios are the SSP-2 scenarios and the Current Policies scenario from the World Energy Outlook (IEA 2019). They can both be considered policies-as-usual scenarios with middle-of-the-road expectations on population growth and economic development, but there are still some differences between the two (Table 12.1). The net emission reduction potentials reported here were generally based on analysis carried out before 2020, so the impact of the COVID-19 pandemic was not taken into account. For comparison, the Stated Policies scenario of the World Energy Outlook 2020 (IEA 2020a) is also shown, one of the few scenarios in which the impact of COVID-19 was taken into account. For the pre-2020 scenarios variation up to 10% between the different baselines exist. The potential estimates presented later should be seen against this background. The total emissions under a current policy scenario in 2030 are expected to be somewhere in the range 57 – 70 $GtCO_2$-eq (Table 4.1, Chapter 4).

For the sector Buildings the current policy scenario of World Energy Outlook 2020 (IEA 2020a) was used as a baseline. For the Agriculture, Forestry and Other Land Use (AFOLU) sector, the potentials were derived from a variety of studies. It may be expected that the best estimates – as averages – match with the current policy baselines in a middle-of-the-road scenario. For the Industry sector, an own baseline was developed, with emissions that may be slightly higher than in the Current Policies scenario of WEO-2019. For the Energy sector the provisional data are based on the World Energy Outlook of 2016 (IEA 2016), which started from about 3% higher CO_2 emissions for 2030 than the World Energy Outlook 2019 (IEA 2019).

Table 12.1 Key characteristics of scenarios that are representative of middle-of-the-road policies-as-usual scenarios used as baselines for determining costs and potentials. The values are for the year 2030 (IEA 2019; IEA, 2020; IIASA 2018).

	SSP2 baseline (MESSAGE-GLOBIOM)	All baseline scenarios median (25/75 per-centiles in parenthesis)	WEO-2019 (Current Policies)	WEO-2020 (Stated Policies)	AR6 Chapter 4 (Current Policies)
Real GDP (PPP) (10^{12} USD)	158 (USD$_{2010}$)	159 (156-171)	3.6% p.a.↑ (2018 – 2030)	2.9% p.a.↑ (2019 – 2030)	
Population (billion)	8.3	8.30 (8.26 – 8.39)	8.6		
Total primary energy use (EJ)	627	675 (636 – 712)	710	660	
Total final energy use (EJ)	499	491 (461-519)	502	472	
Energy-related CO_2 emissions (Gt)	33.0	39.4 (35.4-42.7)	37.4	33.2*	38.9 (35-45.2)
CO_2 emissions energy and industry (Gt)	37.9	42.5 (39.3-45.9)		36.0	
Total CO_2 (emissions Gt)	40.6	45.7 (40.6 – 49.5)			45.5 (40.1-51.5)
Total greenhouse gas emissions ($GtCO_2$-eq)	52.7	62.1 (57.8 – 66.3)			62.9 (57.3-69.8)

*) The difference between WEO-2020 and WEO-2019 is partly explained by the fact that WEO-2019 had two different baselines: Current Policies and Stated Policies. The latter had energy-related emissions 34.9 $GtCO_2$.

12.2.2 Aggregate costs and potentials for 2030

An overview of net emission reduction potentials for different mitigation options is presented in Table 12.2. Some of the options influence each other or are mutually exclusive, so the numbers for individual mitigation actions cannot be aggregated.

For the potentials in the Energy sector, information on net emission reduction potentials was obtained from an earlier report (UNEP, 2017), but cost levels were newly analysed by the authors of Chapter 6, these are combined in the table. For the AFOLU sector a large number of global net emission reduction studies were analysed by the Chapter 7 team. From these studies, emission reduction ranges and best estimates were derived. The variety of studies was not only for the year 2030, but part of them were valid for the entire time period 2020 – 2050. However, because most of the activities involve storage of carbon in stocks that accumulate carbon, or conversely decay over time (e.g., forests, mangroves, peatland soils, agricultural soils, wood products) the 2020-2050 average provides a good approximation of the amount of permanent atmospheric CO_2 mitigation that could be available at a given price in 2030. The exception is BECCS which is in an early upscaling phase. Therefore, a best estimate at the lower end of the range was selected (note that the Energy sector and the Industry sector also provide BECCS potentials, this will be discussed later). The emission reduction potentials for the building sector were based on the analysis by Chapter 9 authors of a large number of bottom-up studies for individual countries. Most of these studies targeted 2050 for the decarbonisation of buildings; the potentials in 2030 reported here are interpolated estimates targeting these 2050 figures. Based on these individual country studies, regional aggregate emission reduction percentages were found. These were subsequently applied to the regional data of the Current Policies Scenario of the World Energy Outlook. For the transport sector, some data from Chapter 10 were used, but they have been complemented by additional sources to achieve a complete overview of emission reduction potentials. For the industrial sector, global emission reduction potentials per technology class were derived per sector by Chapter 11 authors, based on a literature assessment. In the table below, they were aggregated to the entire manufacturing industry. Data for some CDR options were taken from Chapter 12 (Section 12.3). Additional sources (Purohit and Höglund-Isaksson 2017; Höglund-Isaksson et al. 2020) were used for some emission sources not covered elsewhere (coal mining, oil and gas operations, waste and cross-sectoral HFC emissions). For more details about data sources and data processing, see Supplementary Material 12.A. Section SM 12.A.2.

Table 12.2 Detailed overview of net GHG emission reduction potentials ($GtCO_2$-eq) in the various cost categories. Note that potentials cannot be simply counted together, as the adoption of some options may affect the mitigation potentials of other options. Ranges are indicated in parenthesis; they reflect full ranges.

Emission reduction options (includes carbon sequestration options)	**Cost categories (USD tCO_2-eq^{-1})**					**Notes**
	<0	**0–20**	**20–50**	**50–100**	**100–200**	
Energy sector						*The potentials provided for the electricity sector (wind energy ... BECCS) are indicative and should be considered as a placeholder. Analysis from Chapter 6 shows that it is difficult to determine an upper limit for the potentials in the energy sector.*
Wind energy	1.3 – 2.1	1.3 – 2.1				
Solar energy		1.5 – 3.0	1.5 – 3.0			
Nuclear energy			0.44	0.44		
Bioenergy		0.43	0.43			
Hydropower			0.16	0.16		
Geothermal energy		0.37	0.37			
CCS				0.27	0.27	
Bioenergy with CCS				0.2	0.1	
CH_4 emission reduction from coal mining	0.01	0.30	0.03	0.02		
CH_4 emission reduction from oil and gas operations	0.65	0.27	0.25			
Land-based mitigation options (including agriculture and forestry)						*Potentials for AFOLU are rather averages for the period 2020–2050 than specific for the year 2030. Most likely, these values can already be achieved in 2030.*
Carbon sequestration in agriculture (soil carbon, agroforestry and biochar)		1.1 (0.9 – 1.8)	0.6 (0.3 – 0.6)	0.2 (0.15 – 0.5)		Additional technical potential: 3.7 (possibly much higher)
CH_4 and N_2O emission reduction in agriculture		0.3 (0.2 – 1.1)	-	0.1 (0.05 – 0.3)		Additional technical potential: 1.3 GWPs used unknown
Reducing deforestation Reforestation and afforestation		1.8 (1.4 – 2.7)	2.0 (1.5 – 2.7)	1.1 (0.9 – 1.3)		Additional technical potential 0.2 (possibly much higher)
Other land-uses change options, e.g. fire prevention, peatland restoration		1.2 (0.9 – 1.6)				
Bioenergy with CCS				0.8		Additional technical potential: 4.0.

Emission reduction options (includes carbon sequestration options)	**Cost categories (USD tCO_2-eq^{-1})**					**Notes**
	<0	**0–20**	**20–50**	**50–100**	**100–200**	
				(0.8 – 3.5)		Note that also in the Energy sector and Industry, mitigation potentials are given for BECSS. The potential listed here will therefore not be included in the total for land-based mitigation options.
Increased use of wood products (e.g. in construction)						Technical potential 0.5 (0.1 – 1)
Reduce food loss and food waste						Technical potential 2.1 (0.1 – 5.8)
Shift to sustainable healthy diets						Technical potential 4.3 (0.5 – 8) Feasible potential 1.8 (0.3 -3.9)
Buildings						
More efficient appliances, equipment, and lighting	1.0					
Envelope insulation, HVAC systems, water heating and other options to reduce thermal energy use, existing buildings			1.3			
Envelope insulation, HVAC systems, water heating and other options to reduce thermal energy use, new buildings		0.8				
Rooftop photovoltaic systems, heat from solar energy and bio-energy	0.7					
Sufficiency options			At least 0.7			No data available to estimate the cost of sufficiency options
Transport						
LDV – fuel efficiency	0.5					
LDV – electric vehicles	0.4 – 0.5					
LDV – shift to public transport	0.5					
LDV – shift to bikes and e-bikes	0.2					
HDV – fuel efficiency	0.5					
HDV – electric vehicles	0.2					
HDV – shift to rail						No data available.

Emission reduction options (includes carbon sequestration options)	**Cost categories (USD tCO$_2$-eq^{-1})**					**Notes**
	<0	**0–20**	**20–50**	**50–100**	**100–200**	
Shipping – efficiency, optimisation, biofuels	0.5 (0.2–0.7)		0.2 (0.1–0.3)			
Aviation – energy efficiency	0.12 – 0.32					Limited evidence
Reduce flying						No estimate of the global potential available, but important option at individual level (5.3.1.2)
Biofuels			0.6 – 0.8			Overlaps with biofuels for shipping
Industry						*The numbers for the Industry sector typically have an uncertainty of ±25%. The numbers are corrected for overlap between the options, i.e. they can be counted together to provide full potentials.*
Energy efficiency – fuels		1.1	0.37			
Energy efficiency – electricity						No data available
Material efficiency			0.85			
Enhanced recycling			0.55			
Fuel switching to electricity and natural gas			0.76			
Electrification			0.53	0.53		
Bioenergy				0.29	0.15	
CCS, hydrogen etc.				0.23	0.15	
Cement industry: alternative feedstock			0.28			
Reduction of non-CO$_2$ emissions		0.2				
Other						
Reduction of HFC emissions	0.5	0.9	0.1			GWPs not updated
Reduction of CH$_4$ emissions from solid waste	0.51	0.04	0.04	0.03	0.02	
Reduction of CH$_4$ emissions from wastewater	0.06	0.07	0.09	0.04		
Direct air carbon capture and storage					<< 1	There is potential in these categories, but given the current TRL levels, for 2030 the potential is limited. Also, it is not certain whether the costs will already drop below 200 USD tCO$_2^{-1}$ before 2030. In the longer term, much larger potentials are projected, see Section 12.3.1.
Enhanced weathering					<< 1	

As suggested previously, the overview presented in Table 12.2 should be interpreted with care, as the implementation of one option may affect the mitigation potential of another option (see Section 12.6). In addition, they do not all have similar baselines. Nevertheless, a number of major options can be discerned, including solar energy and wind energy, carbon sequestration in agriculture, forestry-related options, thermal improvement of buildings, more efficient equipment for the building sector and HFC emission reductions, all at low to medium costs. Note that for some sectors, like transport and industry, the potential is presented in a more disaggregated way, but in total for these sectors very substantial potential is also available, for transport at low, and for industry at medium costs.

Table 12.3 provides an overview of aggregated mitigation potentials per sector. Note that sectoral aggregates for AFOLU were taken directly from Table 7.4 from Chapter 7 (not from Table 12.3). A mid-range estimate is not presented, but after correcting for overlap and taking into account uncertainties in the individual values (more details in the Supplementary Material SM 12.A., Section SM 12.A.3), the total emission reduction potential at costs below 100 USD tCO_2eq^{-1} would be in the range of 30 – 40 $GtCO_2$-eq. This number excludes the emission reductions that can be achieved through demand side measures related to the AFOLU sector. Given the baseline emissions of 57 – 65 $GtCO_2$-eq in 2030, the total potential is *likely* sufficient to bring down total emissions in 2030 to below half of the present (2018) value of 59 $GtCO_2$-eq. Looking at the costs, of all the options listed in Table 12.2 about 60% comes at low costs: smaller than 20 USD tCO_2^{-1}. Low cost options are dominating in all sectors, except industry.

In this analysis, the emphasis is on the specific mitigation costs of the various options, and these are often considered as an indicator to prioritise options. However, in such a prioritisation, also other elements will play a role, like the development of technology for the longer term (see Section 12.2.4) and the need to optimise investments over longer time periods, see e.g. (Vogt-Schilb et al. 2018) who argue that sometimes it makes sense to start with most expensive option.

Table 12.3 Overview of aggregate sectoral net GHG emission reduction potentials in the various cost categories and comparison with earlier studies. Note that sectors are not entirely comparable across the three different estimates.

Sector	**Mitigation potentials at costs less than 100 USD tCO_2-eq^{-1}**				
	AR6 best estimate	AR6 range	AR4, 2007	UNEP, 2017 best estimate	UNEP, 2017 range
Electricity sector	11.1	8.9 – 11.1	6.2 - 9.3	12.5	11.2 – 13.4
Other energy sector	1.5				
Agriculture	2.3	1.7 – 3.6	2.3 - 6.4	4.8	3.6 – 6.0
Forestry and other land-use change	6.8	5.0 – 8.7	1.3 - 4.2	5.3	4.1 – 6.5
AFOLU demand-side options	7.3	1 - 18			1.3 – 3.4
Buildings demand-side options, excluding sufficiency	Dir 1.2 Ind 2.6 Tot 3.8	±25%	Dir 2.3 - 2.9 Ind 3.0 – 3.8 Tot 5.4 – 6.7	Dir 1.9 Ind 4.0 Tot 5.9	Dir 1.6 – 2.1

Transport	3.8	±25%	1.6 - 2.5	4.7	4.1 - 5.3
Industry	Dir 5.7	±25%	Dir. 2.3 - 4.9 Ind. 0.83 Tot 3.1 - 5.7	Dir 3.9 Ind 1.9 Tot 5.8	Dir. 3.0 – 4.8
HFC emissions (all sectors)	1.5		NE	1.5	1.2 – 1.8
Other	0.9		0.4 - 1.0	1.4	
Total of all sectors	30 – 40*		15.8 - 31.1	38	35 - 41

Dir = reduction of direct emissions, Ind = reduction of indirect emissions (related to electricity production), Tot = reduction of total emissions, NA = not applicable, NE = not estimated, AR4: Table 11.3, UNEP, 2017 = Emissions gap report 2017, Chapter 4.

(*) Total excludes demand side measures related to the AFOLU sectors.

Costs and potentials for 2030 have been presented previously, notably in the 4th Assessment Report (AR4) of the IPCC (Barker et al. 2007) and the Emissions Gap Report (UNEP 2017). The aggregated potentials reported here are higher than those estimated in AR4. Note however, that AR4 suggested the potentials were underestimated by 10 – 15%, but still a higher potential remains in the current assessment. The potentials reported here are comparable with UNEP (2017) (note though that for the Energy sector and for HFC emissions, the data from UNEP (2017) were reused in the current overview). Also, McKinsey (2009) presents a marginal abatement cost curve for 2030, which also represents costs and potentials, suggesting a total potential of 38 $GtCO_2$-eq, but starting from 15% higher baseline emissions.

If we look on a sector-by-sector basis we see somewhat more modest potential estimates for the agricultural sector and the buildings sector, and higher estimates for the energy sector and industry. For the electricity sector a possible explanation is higher estimates for wind and solar energy. For the industry sector, the explanation for the higher potential may be the inclusion of new options, like material efficiency and recycling. For the buildings sector, the explanation is that the 2030 baseline emissions in developed, transition, and developing countries were estimated substantially higher in AR4 than these respective emissions in AR6.

12.2.3 Comparison between sectoral results and results from integrated assessment models

This section compares the sectoral results summarised above and the emissions reductions from integrated assessment models (IAMs). Data were taken from the IPCC AR6 Scenario database. A high-level comparison per sector is provided in Figure 12.2. All scenarios that are "well below 2°C" are included for the comparison (C1, C2, C3).

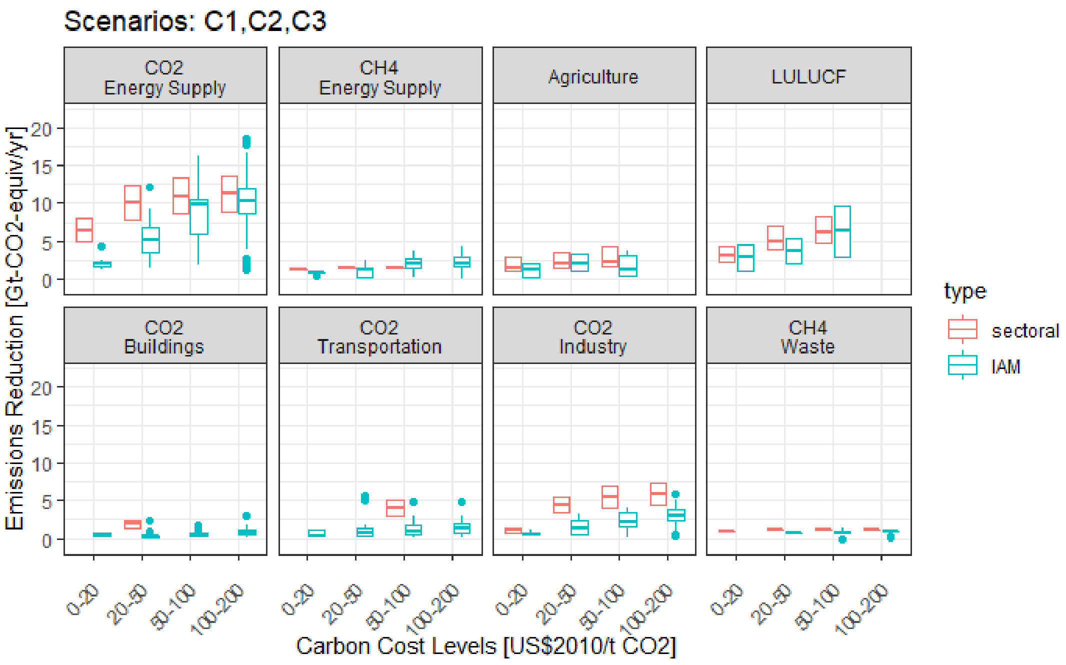


Figure 12.2 Comparison of sectoral estimates for the emission reduction potential with the emission reductions calculated using Integrated Assessment models. The latter are given as box plots of global emissions reduction for each sector (blue) at different carbon price levels (horizontal axis) for 2030, based on all C1, C2 and C3 scenarios in the IPCC AR6 scenario database (https://data.ene.iiasa.ac.at/ar6-scenario-submission/). Outliers of each box plot are represented as dots. In red, the estimates from the sectoral analysis are given. In all cases, only direct emission reductions are presented.

For the energy supply sector, the emission reductions projected by the IAMs are comparable with the potentials found in the sectoral analysis. The only difference is that the sectoral studies find that cheaper options are available to what is assumed in the IAMs (note, however, that the scenario database comprises studies from 2014). A more detailed comparison for the power sector is given in Figure 12.3. Both the sectoral analysis and the IAMs find a dominant role for solar and wind energy, complemented with growth in a range of other technologies.

For the AFOLU sector, the sectoral studies provide net emission reduction potentials comparable with projections from the IAMs. This is, however, only the case if demand side options are excluded. Demand side options, which are likely to only be represented to a limited extent in the IAMs, could play an important role in mitigating greenhouse gas emissions.

For the buildings and transport sector, the sectoral emission reduction potentials are substantially higher than those projected by the IAMs.

For the industry sector, the sectoral emission reduction potentials are typically double those reported on average by IAMs. A likely explanation for the difference is the inclusion of recycling and material efficiency in the sectoral analysis, which are not included in the IAMs.

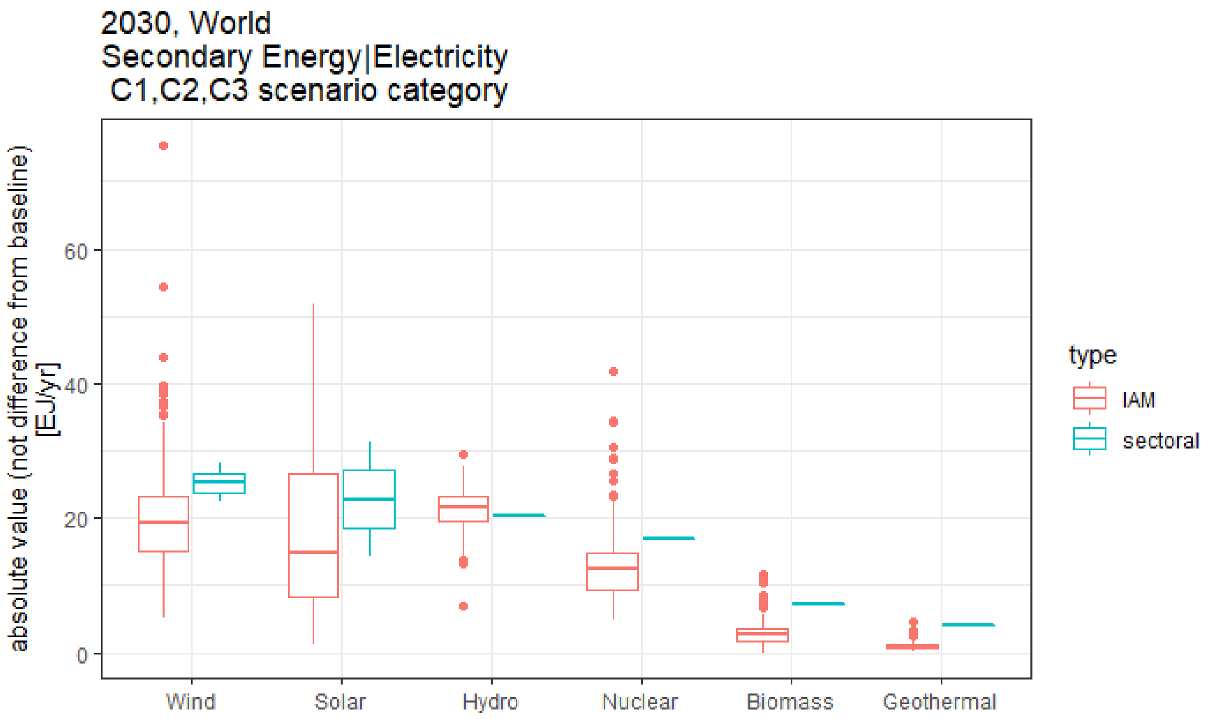


Figure 12.3 Electricity production as calculated by Integrated Assessment Models (blue), compared with electricity production potentials found in the sectoral analysis (red). In both cases cost cut-offs at 100 USD tCO_2^{-1} are applied.

12.2.4 Sectoral findings on emission pathways until 2050

As noted previously, a more qualitative approach is followed and less quantitative information is presented for 2050. The sectoral results are summarised in Table 12.4. In addition to the many technologies that already play a role by 2030 (see Table 12.1) additional technologies are required, for example for managing power systems with high shares of intermittent renewable sources and for providing new fuels and associated infrastructure for sectors that are hard to decarbonise. New processes also play an important role, notably for industrial processes. In general, stronger sector coupling is needed: the increased integration of energy end-use and supply sectors with one another.

1 **Table 12.4 Emission reduction options and their characteristics for 2050 [Preliminary version]**

Sector	Major options	Complementary options	Specific costs*	Degree to which zero-GHG is possible
Energy sector	Range of supply side options possible (see 2030 overview). Increased share of electricity in final energy use Potentially important role for hydrogen, ammonia, etc.	Flexible generation Grid interconnection Demand response Energy storage Shift from asset redundancy to digitalisation (6.2.6.2)	Low to intermediate: lower if sufficient use is made of complementary options (6.2.6.3)	Zero CO_2 energy system is possible
Agriculture, forestry and other land use	Options comparable to those in 2030. Permanence is important.		Low to intermediate	Some hard-to-abate activities will still have positive emissions, but for the sector as a whole, negative emissions are possible through carbon sequestration in agriculture and forestry
Buildings	Sufficiency, high performance new and existing buildings with efficient HVAC esp. heat pumps, efficiency appliances, onsite renewables		Low to intermediate	Approx. 80% reduction is possible with options on demand-side. Nearly net-zero is possible if grid electricity will also be decarbonised.
Transport				
Industry	Stronger role for material efficiency and recycling. Full decarbonisation through new processes, CCUS, hydrogen can become dominant		Intermediate	Approx. 85% reduction is feasible. Net-zero is possible with retrofitting and early retirement.

Non-sectoral	Direct air carbon capture and storage Enhanced weathering		Intermediate to high	Only negative emissions

* Cost indications: Low: less than 20 USD tCO_2-eq^{-1}; Intermediate: 20-100 USD tCO_2-eq^{-1}; High: more than 100 USD tCO_2-eq^{-1}

12.3 CO_2 removal (CDR) options

CDR refers to a cluster of technologies, practices, and approaches that remove and sequester carbon dioxide from the atmosphere and durably store the carbon in geological, terrestrial, or ocean reservoirs, or in products. Despite the common feature of removing carbon dioxide, these technologies can be very different (Smith et al. 2017). One can usefully distinguish between ecosystem-based and technological options, and a combination of both. In general, ecosystem-based CDR options are less costly, closer to deployment but more vulnerable to reversal, whereas the technological CDR options tend to have higher costs, higher research, development & demonstration (RD&D) needs but the advantage of more permanent CO_2 storage, such as in geological and ocean inorganic carbon reservoirs (Figure 12.4).

A number of CDR options (e.g., Afforestation/Reforestation (A/R), Bioenergy with Carbon Capture and Storage (BECCS), soil carbon sequestration, biochar, wetland / peatland restoration and coastal restoration) are dealt with elsewhere in this volume (Chapters 6 and 7). These options are synthesised in Section 12.3.3. Others, not dealt with elsewhere, i.e., Direct Air Carbon Capture and Storage (DACCS), enhanced weathering of minerals (EW) and ocean-based approaches including ocean fertilisation (OF) and alkalinity (OA) enhancement, are discussed in Sections 12.3.2.1 to 12.3.2.3 below. The climate system and the carbon cycle responses to CDR are assessed in Chapters 4 and 5 of the WGI report.

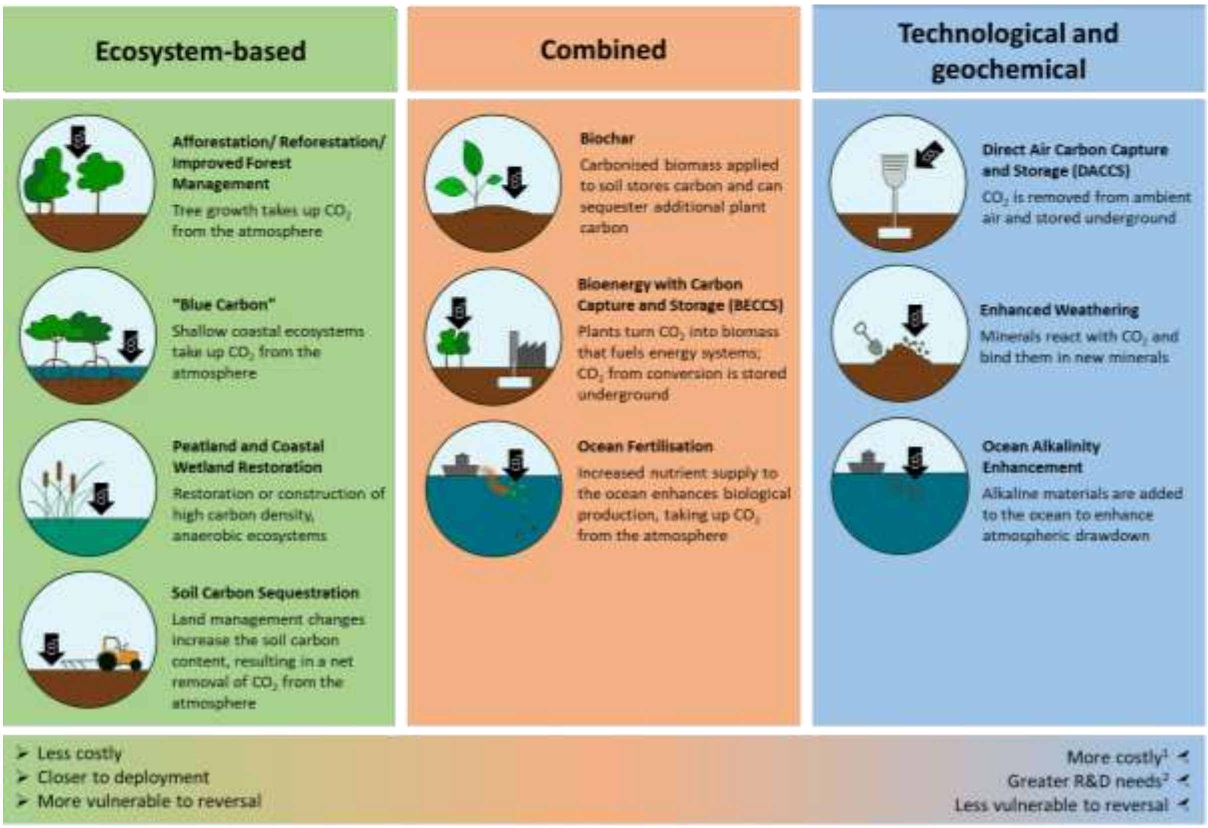


Figure 12.4. Primary options for carbon dioxide removal -updated figure based on figure from Chapter 7 of UNEP Emissions Gap Report 2017 (Smith et al. 2017). Exceptions in general costs and R&D trends are indicated by footnotes: (1) ocean fertilisation is more costly than indicated by the scale and (2) DACCS has a higher TRL whereas "blue carbon" and ocean fertilisation have a lower TRL than according to the scale, see Table 12.6.

12.3.1 State of CDR

CDR can be used to complement two basic mitigation strategies: a) to offset residual emissions hard to abate (e.g. from agriculture, aviation or industrial processes) (Davis et al. 2018; Luderer et al. 2018) in the context of reaching and maintaining *net zero* emissions and b) to prevent or return from temporary overshoots of carbon budgets and temperature thresholds by delivering *net negative* emissions to limit warming to 1.5°C–2°C by 2100, with significantly higher volumes of CDR needed in the latter case (Meadowcroft 2013; Rogelj et al. 2018; van Vuuren et al. 2018; Geden et al. 2019). While many governments have included A/R and other forestry measures into their NDCs under the Paris Agreement (Forsell et al. 2016), none is pursuing a comprehensive CDR strategy so far (Fridahl 2017; Peters and Geden 2017). There are concerns that the prospect of large-scale CDR could obstruct emission reduction efforts (Morrow 2014; Markusson et al. 2018), might lead to an overreliance on technologies that are still in their infancy (Anderson and Peters 2016; Larkin et al. 2018), could overburden future generations (Lenzi 2018; Shue 2018; Bednar et al. 2019) or might be perceived negatively by stakeholders and broader publics (Royal Society and Royal Academy of Engineering 2018; Colvin et al. 2020) – highlighting the need for dedicated CDR governance (Section 12.7.1).

Some biological methods used for CDR (like A/R, wetland restoration and soil-carbon management) have been practiced for decades to millennia. Conversely, for technological approaches such as DACCS, BECCS, and EW, experience is still limited and there are few policies to incentivise their use. Given the lack of CDR policy instruments (Honegger and Reiner 2018a) and the long time periods involved in scaling up and deploying novel technologies, there are many challenges in research, development and demonstration to advance innovation in line with broader societal objectives and bring down costs (Nemet et al. 2018).

The volumes of CDR deployment assumed in IAM-based global emissions mitigation scenarios are significant if compared to current volumes of deployment, given that the feasibility of rapid and sustained upscaling is uncertain (de Coninck et al. 2018). All Illustrative Pathways (IPs) use either land-based CDR or technological CDR, or both, in meeting low-temperature targets of 1.5–2.0°C. In scenarios compatible with limiting the temperature increase to below 2°C by the end of the century (scenario categories of C1-C3; see Chapter 3), annual deployment of technological CDR reaches 0.04 [0.002 – 0.19] $GtCO_2\ yr^{-1}$ by 2030, 3.2 [1.8 -4.5] $GtCO_2\ yr^{-1}$ by 2050 and 10.5 [7.3-13.8] $GtCO_2\ yr^{-1}$ by 2100 (values are the medians and bracketed values denote the interquartile range), and net AFOLU CDR reaches 0.7 [0.24-2.4] $GtCO_2\ yr^{-1}$, 2.2 [1.0-4.9] $GtCO_2\ yr^{-1}$, and 3.2 [0.8-4.9] $GtCO_2\ yr^{-1}$ for these years, respectively (Figure 12.5). Cumulative volumes of BECCS/DACCS/EW CDR, AFOLU, and total CDR reach 428 [311-537] $GtCO_2$, 221 [209-279] $GtCO_2$, and 551 [375-734] $GtCO_2$ for the 2016-2100 period, respectively. Depending on assumptions on residual emissions, cumulative CDR volumes of 128 and 211 $GtCO_2$ are needed to reach a balance between emissions and removals for reaching net-zero CO_2 emissions for 1.5 and 2.0 °C targets, respectively (values are the medians and based on the AR6 scenario database). New studies have identified some reasons for large-scale CDR deployment, including some barriers to VRE deployment, a high discount rate, among others (Köberle 2019; Emmerling et al. 2019; Hilaire et al. 2019).

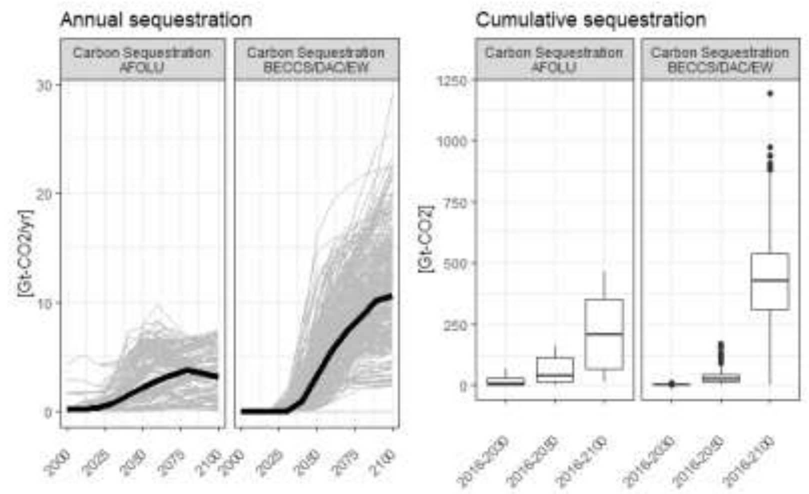


Figure 12.5. Sequestration of two predominant CDR categories: BECCS-DAC-EW and AFOLU (left two panels) annual sequestration and (right two panels) cumulative sequestration. The scenarios correspond to C1 (C1: 1.5°C with no or low OS), C2 (C2: 1.5°C with high OS), and C3 (lower 2°C) scenario categories.

While many methods are gradually being explored, IAM scenarios have focused mostly on BECCS and A/R (Tavoni and Socolow 2013; Tavoni et al. 2017; Rickels et al. 2019), some studies did explore other options such as DACCS (Chen and Tavoni 2013; Marcucci et al. 2017) and enhanced weathering (Strefler et al. 2018) and other methods (Holz et al. 2018) but the literature remains small compared to that on BECCS (Hilaire et al. 2019). In fact, a large-scale, coordinated study exists on bioenergy (e.g., Stanford Energy Modeling Forum 33 in Bauer et al. 2018) but none exists for other types of CDR techniques. A small number of techno-economic assessments on CDR techniques other than bioenergy / forestry options could explain the lack of scenarios based on other techniques. A recent review advocates for a combination of various CDR approaches (Fuss et al. 2018) but the scenario literature on such a mixed CDR approach is yet to emerge.

At the national and regional level, the role of ecosystem-based CDR methods has long been analysed, but compared with other types of analyses, there is little detailed technoeconomic assessment of the role of other CDR in national/regional mitigation, though there is an small but emerging literature (Baik et al. 2018; Sanchez et al. 2018; Patrizio et al. 2018; Rhodium Group 2019; Daggash et al. 2018; Kato and Kurosawa 2019; Kraxner et al. 2014; Breyer et al. 2019a; McQueen et al. 2020).

A major gap exists between the CDR volumes assumed/reported in IAM's global emission scenarios and sectoral mitigation pathways, where substantial CDR levels are only to be found in the AFOLU and the energy conversion sector, and to a lesser extent in the transport and industry sectors. Several CDR options currently not covered by IAMs are not directly embedded in sectoral production/consumption process. Carbon removal realised through options like DACCS, Enhanced Weathering or Ocean-based approaches (see Section 12.3.2) cannot directly be attributed to distinct sectors. Furthermore, expectations for providing sufficient levels of research, development and demonstration cannot rely on existing industrial actors.

12.3.2 CDR technologies not covered elsewhere in this report: DACCS, enhanced weathering and ocean-based approaches

12.3.2.1 DACCS

DACCS shares with conventional CCS the storage component but is distinct in its capture part. Capturing the CO_2 involves three basic steps: a) contacting the air, b) capturing on a liquid or solid sorbent or a liquid solvent, c) regeneration of the solvent or the sorbent (with heat, moisture and/or pressure). After capture, the CO_2 stream can be stored underground or utilised. The duration of storage is an important consideration; geological reservoirs or mineralisation result in permanent removal. The efficiency of CO_2 removal depends on the carbon intensity of the energy input (electricity and heat) and other LCA considerations (Jacobson 2019). Utilisation of captured CO_2 (DACCU) (Breyer et al. 2019b) to produce synthetic fuels, building materials or plastics may not have a long-term removal effect, depending on the lifetime of respective products (Lackner et al. 2012; Wilcox et al. 2017; Fuss et al. 2018; Gunnarsson et al. 2018; Bui et al. 2018; Creutzig et al. 2019; Royal Society and Royal Academy of Engineering 2018) with the lifetime varying from centuries for building concrete materials (Hepburn et al. 2019) to millennia for carbon fibre.

DAC (direct air capture) methods can be differentiated by the chemical processes used to capture ambient CO_2 from the air and recover it from the sorbent (Fasihi et al. 2019). The main categories are a) liquid solutions with high-temperature regeneration, b) solid sorbents with low temperature regeneration and c) regenerating by moisturing of solid sorbents. Compared to other CDR methods, the primary barrier to upscaling DAC is its high cost (Nemet et al. 2018), which can be reduced through innovations. It has therefore attracted entrepreneurs and private investments, albeit at a small scale.

Status: There are some demonstration projects by start-up companies and academic researchers, who are developing various types of DAC, including aqueous potassium solvent with calcium carbonation and solid sorbents with heat regeneration (National Academies of Sciences Engineering and Medicine 2019). These projects are supported mostly by private investments and grants or sometimes serve for utilisation niche markets (e.g., CO_2 for beverages, greenhouses, voluntary offsets, enhanced oil recovery). As of 2020, there are 15 plants worldwide, whose scale is ~1 $ktCO_2\ yr^{-1}$ or smaller, with the largest designed to capture 4 $ktCO_2\ yr^{-1}$ in Alabama, USA (National Academies of Sciences Engineering and Medicine 2019; Rhodium Group 2019; IEA 2020b). This can be contrasted with a target, mature system of a 1 $MtCO_2\ yr^{-1}$ capture rate, which is three orders of magnitude larger. Because of the fundamental difference in the concentration, DACCS does not benefit directly from RD&D in conventional CCS (National Academies of Sciences Engineering and Medicine 2019). For instance, the air contactor of a liquid-solution technology takes a cross-flow configuration, not the counter-current configuration often used in conventional CCS (Keith et al. 2018; National Academies of Sciences Engineering and Medicine 2019). An RD&D program dedicated to DAC would therefore be required (National Academies of Sciences Engineering and Medicine 2019; Rhodium Group 2019). Possible basic research topics include development of new liquid solvents, novel solid sorbents, and novel equipment or system designs (National Academies of Sciences Engineering and Medicine 2019). National Academies of Sciences (2019) also emphasises the role of third-party evaluation of techno-economic aspects. However, since basic research does not appear to be a primary barrier, both National Academies of Sciences (2019) and Larsen et al. (2019) argue for a stronger focus on demonstration in the US context.

Costs: Since the process captures dilute CO_2 (~0.04%) from the ambient air, it is less efficient and more costly than conventional carbon capture applied to power plants and industrial installations (with a CO_2 concentration of ~10%), which cannot serve as CDR. The cost of a liquid solvent system is dominated by the energy cost (because of the much higher energy demand for CO_2 regeneration, which reduces the efficiency) while capital costs account for a significant share of the cost of solid sorbent systems (Fasihi et al. 2019). The range of the DAC cost estimates found in the literature is wide (60–1000 USD tCO_2^{-}

^{1}) (Fuss et al. 2018) partly because different studies assume different use cases, differing phases (first plant vs. *n*th plant; Lackner et al. 2012), different configurations, and disparate system boundaries. For instance, a DAC cost of 60 USD tCO_2^{-1} might be possible if the purpose is to supply 5% CO_2 concentration for a greenhouse. Estimates of industrial origin are often on the lower side (Ishimoto et al. 2017). Recent studies on plausible system designs with newer data show a range of 60–500 USD tCO_2^{-1} (Sinha et al. 2017; Keith et al. 2018; National Academies of Sciences Engineering and Medicine 2019). Some studies suggest a significant cost decline helped by ever cheaper solar PV (Breyer et al. 2019b).

Potentials: There is no specific study on the potential of DACCS but the literature has assumed that the technical potential of DACCS is virtually unlimited (Marcucci et al. 2017; Fuss et al. 2018; Lawrence et al. 2018) since DACCS encounters less non-cost constraints than any other CDR option. Focusing only on the Maghreb region, (Breyer et al. 2019a) reported an optimistic potential 150 Gt-CO_2 at < 60 euros/t-CO_2 for 2050. Fuss et al. (2018) suggest a potential of <5 $GtCO_2$ yr^{-1} by 2050 because of environmental side effects and limits to underground storage and note that the potential can be expanded to 40 $GtCO_2$ yr^{-1} if these constraints are found to be non-binding. In addition to the ultimate potentials, Realmonte et al. (2019) noted the rate of scale-up as a strong constraint on deployment. More systematic analysis on potentials is necessary, first and foremost on national and regional levels, including the requirements for low-carbon heat and power, water and material demand, availability of geological storage and the need for land in case of low-density energy sources such as solar or wind power.

Risks and impacts: DACCS requires a considerable amount of energy, and depending on the type of technology, water, and make-up sorbents. Its land footprint is small compared to other CDR methods (Smith et al. 2016). An important consideration for a DACCS system is the large energy requirement. The theoretical minimum requirement for separating CO_2 from the air is ~0.5 GJ tCO_2^{-1} (Socolow et al. 2011). Fasihi et al. (2019) reviewed the published estimates of energy requirements and found that for the current technology, the energy requirement is 4–10 GJ tCO_2^{-1} (both power and heat combined). At a 10 $GtCO_2$ yr^{-1} sequestration, this would translate into 40–100 EJ yr^{-1} of energy consumption, which can be contrasted with the current primary energy supply of ~600 EJ yr^{-1}. Low-temperature heat could be sourced from renewable-powered heat pumps (Breyer et al. 2019a) or waste heat. Unless sourced from a clean source, this amount of energy could degrade the environment (Jacobson 2019). If sourced from renewables, a large energy demand drive further expansion of renewables (Beuttler et al. 2019), though detailed analysis is lacking. Because DACCS is an open system, water lost from evaporation must be replenished. Water loss varies, depending on technology (including adjustable factors such as the concentration of the liquid solvent) as well as environmental conditions (e.g., temperate vs. tropical climates). For a liquid solvent system, it can be 0–50 tH_2O tCO_2^{-1} (Fasihi et al. 2019). A unit water loss of ~1–10 tH_2O tCO_2^{-1} (Socolow et al. 2011) would translate into ~10–100 GtH_2O = 10–100km^3 to capture 10 $GtCO_2$ from the atmosphere. Some solid sorbent technologies actually produce water as a by-product, e.g. 0.8–2 tH_2O tCO_2^{-1} for a solid-sorbent technology with heat regeneration (Fasihi et al. 2019; Beuttler et al. 2019). Large-scale deployment DACCS would also require a significant amount of materials. Hydroxide solutions are currently being produced as a by-product of chlorine but replacement (make-up) requirement of such materials at scale upends the market (Realmonte et al. 2019). The land requirements for DAC units are not large. Furthermore, these can be placed on unproductive lands, in contrast to biomass-based approaches. Nevertheless, to ensure that CO_2-poor air does not enter the air contactor of an adjacent DAC system, there must be enough space between DAC units, similar to wind power turbines. Considering this, Socolow et al. (2011) estimated a land footprint of 1.5 km^2 $MtCO_2^{-1}$. On the other hand, large energy requirements lead to significant footprints if low-density energy sources (e.g., solar PV) are used (Smith et al. 2016).

Co-benefits: DAC plants are increasingly discussed as a Power-to-X technology that could use excess renewable power, thereby helping to avoid curtailment of wind and solar PV installations during periods of low demand or caused by transmission congestion (Wohland et al. 2018). However, if DAC plants would be expected to run only when surplus renewable power is available (to take advantage of low or even negative prices), installations would need to be designed for intermittent operations (i.e. at low load factors) which would negatively affect capital and operation costs (Sandalow et al. 2018; Daggash et al. 2018) as a high time-resolution model suggests a high utilisation rate (Breyer et al. 2019a). Solid sorbent DAC designs remove more water from the ambient air than needed for regeneration, thereby delivering surplus water that would contribute to SDG 6 (*Clean Water and Sanitation*) in arid regions (Fasihi et al. 2019; Sandalow et al. 2018). These aspects are yet to be fully explored in IAMs.

Trade-offs and spill over effects: Liquid solvent DAC systems need substantial amounts of water (Fasihi et al. 2019), albeit much less than BECCS systems (Smith et al. 2016), which could negatively affect SDG 6 (*Clean Water and Sanitation*). Although the high energy demand of DACCS could affect SDG 7 (*Affordable and Clean Energy*) negatively through potential competition or positively through learning effects (Beuttler et al. 2019), its impact has not been thoroughly assessed yet. Status, costs, potentials, risk and impacts, co-benefits, trade-offs and spill over effects and the role in mitigation pathways of DACC are summarised in Table 12.6.

Role in mitigation pathways: There are a few IAM studies that have explicitly incorporated DACCS. Chen and Tavoni (2013) looked into the role of DACCS in an IAM (WITCH), and found that incorporating DACCS in their IAM reduces the overall cost of mitigation and tends to postpone the timing of mitigation. The scale of capture goes up to 37 $GtCO_2$ yr^{-1} in 2100. Marcucci et al. (2017) ran MERGE-ETL, an integrated model with endogenous learning, and showed that DACCS allows for a model solution for the 1.5°C target, and that DACCS substitutes for BECCS. In their analysis, DACCS captures 38.3 $GtCO_2$ yr^{-1} in 2100. Realmonte et al. (2019) modelled two types of DACCS (based on liquid and solid sorbents) with two IAMs (TIAM-Grantham and WITCH), and showed that in deep mitigation scenarios, DACCS complements, rather than substitutes, other CDR methods such as BECCS, and that DACCS is effective at containing mitigation costs. At the national scale, (Rhodium Group 2019) utilised the Regional Investment and Operations (RIO) Platform coupled with the Energy PATHWAYS model, and explicitly represented DAC in US energy systems scenarios. They found that in a scenario that reaches net zero emissions by 2045, 0.6 $GtCO_2$ or 1.8 $GtCO_2$ of DACCS would be deployed, depending on the availability of natural carbon sinks and bioenergy.

Status, costs, potentials, risk and impacts, co-benefits, trade-offs and spill over effects and the role in mitigation pathways of DACCS are summarised in Table 12.6.

12.3.2.2 Enhanced weathering

Enhanced weathering involves a) the mining of rocks containing minerals that naturally absorb CO_2 from the atmosphere over geological timescales (as they become exposed to the atmosphere through geological weathering), b) the comminution of these rocks to increase the surface area, and c) the spreading of these crushed rocks on soils (or in the ocean; 12.3.2.3) so that they absorb atmospheric CO_2 (Schuiling and Krijgsman 2006; Hartmann et al. 2013; Beerling et al. 2018). Construction waste, and waste materials (e.g. slag, overburden) can also be used as a source material for enhanced weathering. Silicate rocks, containing minerals rich in calcium and magnesium and lacking metal ions such as nickel and chromium (e.g. basalt), are most suitable for enhanced weathering (Beerling et al. 2018), which reduce soil solution acidity during dissolution, and promote the chemical transformation of CO_2 to bicarbonate ions. The bicarbonate ions may precipitate in soils and drainage waters as a solid carbonate mineral (Manning 2008), or remain dissolved and increase alkalinity levels in the ocean (Renforth and Henderson 2017).

Status: Enhanced weathering has been demonstrated in the laboratory and in small scale field trials but is yet to be demonstrated at scale (Beerling et al. 2018). The chemical reactions are well understood (Gillman 1980; Gillman et al. 2001; Manning 2008), but the behaviour of the crushed rocks in the field and potential co-benefits and adverse-side effects of enhanced weathering require further research

(Beerling et al. 2018). Uncertainty surrounding silicate mineral dissolution rates in soils, the fate of the released products, the extent of overburden legacy reserves that might be exploited, location, availability, of rock extraction sites, and the impact on ecosystems remain poorly quantified and require further research to better understand feasibility (Beerling et al. 2018; Renforth 2012; Moosdorf et al. 2014). Closely monitored, large-scale demonstration projects would allow these aspects to be studied (Smith et al. 2019b; Beerling et al. 2020).

Costs: Fuss et al. (2018), in a systematic review of the costs and potentials of CDR options including enhanced weathering, note that costs are closely related to the source of the rock, the technology used for rock grinding and material transport (Hartmann et al. 2013; Renforth 2012; Strefler et al. 2018). Due to differences in the methods and assumptions between studies, literature ranges are highly uncertain and range from 15–40 USD tCO_2^{-1} to 3460 USD tCO_2^{-1} (Köhler et al. 2010; Taylor et al. 2016). Renforth (2012) reported operational costs in the UK of applying mafic rocks (rocks with high magnesium and iron silicate mineral concentrations) of 70–578 USD tCO_2^{-1}, and for ultramafic rocks (rocks rich in magnesium and iron silicate minerals but with very low silica content - the low silica content influences weathering rates in a positive way) of 24–123 USD tCO_2^{-1}. The estimates reported in Smith et al. (2016) are based on those of Renforth (2012).

Potentials: In a systematic review of the costs and potentials of enhanced weathering, Fuss et al. (2018) report a wide range of potentials. The highest reported regional sequestration potential, 88.1 $GtCO_2$ yr^{-1}, is reported for the spreading of pulverised rock over a very large surface area in the tropics (Taylor et al. 2016). Considering cropland areas only, the potential carbon removal was estimated by Strefler et al. (2018) to be 95 $GtCO_2$ yr^{-1} for dunite and 4.9 $GtCO_2$ yr^{-1} for basalt. Slightly lower potentials were estimated by Lenton (2014) where the potential of carbon removal by enhanced weathering (including adding carbonate and olivine to both oceans and soils) was estimated to be 3.7 $GtCO_2$ yr^{-1} by 2100, but with mean annual removal an order of magnitude less at 0.2 GtC-eq yr^{-1} (Lenton 2014). The estimates reported in Smith et al. (2016) are based on the potential estimates of Lenton (2014).

Risks and impacts: Mining of rocks to be used for enhanced weathering will have local impacts, and carries the risks associated with the mining of any mineral. In addition to direct habitat destruction and increased traffic to access mining sites, there could be adverse impacts on local water quality (Younger and Wolkersdorfer 2004). These risks, however, need to be offset against the potential, in some cases, for poverty reduction through employment in mining (Pegg 2006).

Co-benefits: Enhanced weathering could enhance soil carbon sequestration (Beerling et al. 2018), and protect against soil erosion (Wrigth and Upadhyaya 1998) and can improve plant growth by pH modification and by supplying minerals (Kantola et al. 2017; Beerling et al. 2018) and increasing the cation exchange capacity, resulting in increased nutrient retention and availability (Baldock and Skjemstad 2000; Yu et al. 2017; Guntzer et al. 2012; Tubana et al. 2016; Manning 2010; Smith et al. 2019b; Haque et al. 2019; Gillman 1980; Gillman et al. 2001). Through these actions, it can contribute to the UN SDGs 2 *Zero Hunger,* 15 *Life of Land* (by reducing land demand for croplands), 13 *Climate Action* (through CDR), 14 *Life Below Water* (by ameliorating ocean acidification) and 6 *Clean Water and Sanitation* (Smith et al. 2019b). To more directly ameliorate ocean acidification while increasing CDR and reducing impacts on land ecosystems, alkaline minerals can be directly added to the ocean (12.3.2.3).

Trade-offs and spill over effects: Air quality could be adversely affected by the spreading of rock dust (Edwards et al. 2017), though this can partly be ameliorated by water-spraying (Grundnig et al. 2006). As noted above, any significant expansion of the mining industry would require careful assessment to avoid possible detrimental effects on biodiversity (Amundson et al. 2015). The processing of an additional 10 billion tonnes of rock would require up to 3000 TWh, which would consume approximately 0.1–6 % of global electricity in 2100. This would place an additional, yet marginal, demand on the future energy system. The emissions associated with this additional energy generation may reduce the net carbon removal by up to 30% with present day grid average emissions (IFASTAT 2018), but this efficiency loss would decrease with non-fossil fuel power.

Role in mitigation pathways: Only one study to date has included enhanced weathering in an integrated assessment model to explore mitigation pathways (Strefler et al. 2018).

Status, costs, potentials, risk and impacts, co-benefits, trade-offs and spill over effects and the role in mitigation pathways of enhanced weathering are summarised in Table 12.6.

12.3.2.3 Ocean-based approaches (ocean fertilisation, alkalinity enhancement and blue carbon)

The oceans contain ~38,000 GtC, some 45 times more than the present atmosphere, and oceanic uptake has already consumed close to 40% of anthropogenic C emissions (Sabine and Tanhua 2010) . Oceans are characterised by diverse biogeochemical cycles involving carbon, and ocean circulation has much longer timescales than the atmosphere, meaning that additional anthropogenic carbon could be potentially stored in the deep ocean or on the sea floor for at least near term if not permanent climate benefit. A wide range of marine CDR options have been proposed (Gattuso et al. 2018; Hoegh-Guldberg et al. 2018; GESAMP 2019) including carbon storage in the ocean, ocean pumping (or enhanced upwelling), methane capture destruction modification of downwelling currents (Zhou and Flynn 2005) and regional Arctic ice management (Desch et al. 2017). The most studied are ocean fertilisation, alkalinity enhancement and sequestration of CO_2 by shallow coastal ecosystems, also referred to as "blue carbon". Potential climate response and influence on carbon budget of ocean-based CDR are discussed in Chapter 4 and 5 in WG1 AR6.

Ocean fertilisation (OF). The natural mechanism of carbon transfer from the atmosphere to the deep ocean – the ocean biological pump - removes 4–10 GtC from surface waters annually; however, ~ 90% of this C is released back into the atmosphere within a year (GESAMP 2019). However, the productivity of the ocean is limited in large areas of the ocean by lack of main nutrients (phosphorus and nitrogen). In those areas of the ocean (about 25% of the total area), where the main nutrients are available in sufficient quantities, the limiting factor in the development of phytoplankton is the lack of trace elements, such as iron. Fertilising the water with iron would speed up the growth of phytoplankton and thus uptake of CO_2, some of which would sink into the deep ocean as carbon when the organisms die. So, there is some potential in attempting to boost productivity through intentional nutrients enrichment, as a means to enhance the ocean biological pump. Thus, the CDR technique can be based on two approaches to increasing the productivity of phytoplankton (Minx et al. 2018)- nutrient enrichment and micronutrient enrichment; the third approach highlighted in the GESAMP (2019) is based on fertilisation for fish stock enhancement. Iron fertilisation is best studied to date, but knowledge so far is still inadequate to predict global consequences.

Ocean Alkalinity (OA). Removal of CO_2 from the atmosphere can be achieved by increasing ocean alkalinity ('ocean alkalinity enhancement' or 'artificial ocean alkalinisation') (Renforth and Henderson 2017). This additional alkalinity can be derived from: 1) the dissolution of natural alkaline minerals that are added directly to the ocean, 2) the dissolution of such minerals upstream from the ocean (e.g., 'enhanced weathering' Section 12.3.2.2) and 3) the addition of manufactured alkalinity to the ocean. In the case of 2), minerals are dissolved on land, and the dissolution products are conveyed to the ocean. These processes result in chemical transformation of CO_2 and sequestration as bicarbonate and carbonate ions (HCO_3^-, CO_3^{2-}) in the ocean. Imbalances between the input and removal fluxes of alkalinity can result in changes in global oceanic alkalinity and therefore the capacity of the ocean to store C. Such alkalinity-induced changes in partitioning of C between atmosphere and ocean are thought to play an important role in controlling climate change on timescales of 1000 years and longer (e.g., (Zeebe 2012)). The residence time of dissolved inorganic carbon in the whole ocean is around 100,000 years, which would effectively form a permanent storage reservoir on human timescales. However, this may decrease if alkalinity is reduced by increased formation and export of carbonate minerals from the surface ocean (Renforth and Henderson 2017). However, spontaneous nucleation is strongly inhibited in seawater and carbonate production is thought to be largely biologically controlled (Andersson 2014).

“Blue carbon”. The term was used originally to refer to biological carbon sequestration in all marine ecosystems. Currently it is focused on carbon associated with rooted vegetation in the coastal zone, such as tidal marshes, mangroves and seagrasses. IPCC SROCC (5.5.1) distinguished biologically-driven carbon fluxes and storage in marine systems that are amenable to management between costal ocean and open ocean.

Status: OF has a natural analogue. Periods of glaciation in the geological past are associated with changes in dust deposition of iron into the ocean. Increased formation of phytoplankton was also observed during seasonal removal of dust from the Arabian Peninsula and ash deposition on the ocean surface after volcanic eruptions (Jaccard et al., 2013; Achterberg et al. 2013; Olgun et al. 2013; Martínez-García et al. 2014). Effectiveness of OF is confirmed by a number of field experiments conducted in different areas of the ocean (Trull et al. 2015; Williamson et al. 2012). However, efficiency of OF depends of the region and experimental conditions; downward carbon transport is less than those observed during natural iron fertilisation (Buesseler et al. 2001).

Technologies for increasing OA have been demonstrated by a small number of laboratory experiments (in addition to enhanced weathering, Section 12.3.2.2). The use of enhanced ocean alkalinity for C storage was first proposed by Kheshgi (1995) who considered the creation of highly reactive lime that would readily dissolve in the surface ocean and sequester CO_2. An alternative method proposed the dissolution of carbonate minerals (e.g., $CaCO_3$) in the presence of waste flue gas CO_2 and seawater as a means capturing CO_2 and converting it to bicarbonate ions (Rau and Caldeira 1999; Rau 2011). House et al. (2007)proposed the creation of alkalinity in the ocean through electrolysis. The fate of the stored carbon is the same for these proposals (i.e., HCO_3^- and CO_3^{2-} ions), but the reaction pathway is different. Very few studies have explored the impact of elevated alkalinity on ocean ecosystems, which has largely been limited to single species experiments (Cripps et al. 2013; Gore et al. 2018) and a constrained field study (Albright et al. 2016).

In recent years, there has been increasing research on the potential, effectiveness, risks, and possibility of introducing CO_2 sequestration in shallow coastal ecosystems. About 20% of the countries that have endorsed the Paris Agreement have committed themselves to blue carbon approaches for climate change mitigation in their NDCs and are moving toward measuring blue carbon in inventories. About 40% of those same countries have pledged to use shallow coastal ecosystems to adapt to climate change (Kuwae and Hori 2019).

Efficiency/Potentials: For OF, the theoretical efficiency is expressed as an increase in the mass of organic carbon by 2–20 kg with the introduction of one gram of iron. However, experiments have shown that the real efficiency of the method can be much lower, because much of the produced organic carbon is oxidised in the upper ocean (up to several hundred meters), a significant part of the resulting carbon dioxide can be carried back into the atmosphere. There are significant differences in the ratio of iron added to carbon fixed photosynthetically, and in the ratio of iron added to carbon sequestered across studies (Trull et al. 2015) which has implications both for the success of this strategy, and its cost. Estimates of various authors show that the potentially achievable net absorption rate of CO_2 may be between 1–3 $GtCO_2\ yr^{-1}$, the cumulative absorption by the end of the century will be 100–300 $GtCO_2$ (Ryaboshapko and Revokatova 2015; Minx et al. 2018).

For OA, the ocean has the capacity to store thousands of $GtCO_2$ (cumulatively) without exceeding pre-industrial levels of carbonate saturation (Renforth and Henderson 2017) if the impacts were distributed evenly across the surface ocean. The potential of increasing ocean alkalinity may be constrained by the capability to extract, process, and react minerals (see Section 12.3.2.2); the demand for co benefits (see below); or to minimise impacts around points of addition. Fuss et al. (2018) suggest storage potentials may be between 1–100 $GtCO_2$ yr^{-1}.

For "blue carbon", Froehlich et al. (2019) found a substantial suitable area (ca. 48 million km ^{2}) for seaweed farming, which is largely unfarmed. Within its own industry, seaweed could create a carbon-neutral aquaculture sector with just 14% (mean is 25%) of current seaweed production (0.001% of suitable area). Using seaweed as a food to reduce emissions from agriculture has been proposed but use as food rather than longer lived products would greatly limit C storage and hence its CDR potential.

Potential co-benefits and adverse effects: Co-benefits for OF include a potential increase in fish catches; enhanced biological (Minx et al. 2018) and reduced upper ocean acidification. Potential drawbacks include subsurface ocean acidification, deoxygenation; altered regional meridional nutrient supply, and fundamental alteration of food webs (GESAMP 2019).

For OA, elevated CO_2 in the atmosphere acidifies the ocean, which puts stress on shell forming organisms ('ocean acidification'). Extensive research has been conducted to understand the impact of ocean acidification on marine biota and the global carbon cycle (Doney et al. 2009). Limiting ocean acidification is an important driver for reducing CO_2 emissions. Some have proposed that risk to ecosystems may be limited by the intentional addition of alkalinity to the oceans (Rau et al. 2012; Williamson and Turley 2012; Albright et al. 2016). Given the paucity of research conducted on biological effects of alkalinity addition, further study is required to demonstrate the positive and negative impacts of alkalinity addition on marine ecosystems. The addition rate would have to be enough to overcome mixing of the local seawater with the ambient environment, but not sufficient to detrimentally impact ecosystems. More research is required to assess locations in which this may be feasible, and how such a scheme may operate (Renforth and Henderson 2017).

For "blue carbon", shallow coastal ecosystems have been severely affected by human activity, significant areas have already been deforested or degraded and continue to be denuded. These processes are accompanied by carbon emissions. The conservation and restoration of coastal ecosystems, which will lead to increased carbon sequestration, is also essential for the preservation of basic ecosystem services, and healthy ecosystems tend to be more resilient to the effects of climate change. Seaweeds are also rich in protein and could be potentially benefit for human nutrition or as fertiliser in terrestrial agriculture, or as an industrial or materials feedstock. Globally, the total carbon sequestration rates are estimated in the range of 0.02-0.08 Gt y^{-1} CO_2 for different species (Wilcox et al. 2017; National Academies of Sciences 2019).

Risks and impacts: For OF, several of the mesoscale iron enrichment experiments have seen the emergence of stocks of potential toxic species of diatoms (Silver et al. 2010; Trick et al. 2010). There is also limited evidence of increased concentrations of other GHGs such as methane and nitrous oxide during the subsurface decomposition of the sinking particles from iron stimulated blooms (Law 2008). Impacts on marine biology and food web structure are unknown; changes to nutrient balance; anoxia in subsurface water; probable enhanced production of N_2O and CH_4 (Fuhrman and Capone 1991; DFO 2010; Minx et al. 2018). Potential risks: geopolitical conflict, alteration of marine resources, effects on food supply, difficulties of attribution could lead to (mis-) attribution of side effects.

For OA, the local impact of increasing alkalinity on ocean chemistry can depend on the speed at which the impacted seawater is diluted/circulated and the exchange of CO_2 from the atmosphere (Bach et al. 2019). Air-equilibrated seawater has a much lower potential to perturb seawater carbonate chemistry. However, a seawater with slow air-sea gas exchange, in which alkalinity increases consumes CO_2 from the surrounding water without immediate replenishment from the atmosphere, would increase seawater pH and saturation states and may impact marine biota. It may be possible to use this effect to create conditions to ameliorate ocean acidification (see below). Like enhanced weathering, some proposals may result in the dissolution products of silicate minerals (e.g., Si, Fe, K, Ni) being supplied to ocean ecosystems (Montserrat et al. 2017) and the ecological consequences of this remain poorly understood (Meysman and Montserrat 2017). For "blue carbon", potential risks relate to the high sensitivity of coastal ecosystems to external impacts associated with both degradation and attempts to increase carbon sequestration. Damaged coastal ecosystems may show lower resilience in the long-term, leading to a reversal of carbon sequestration. It is very difficult to determine which emissions and removals are natural and which are anthropogenic for blue carbon approaches.

Costs: Ocean fertilisation costs depend on nutrient production and its delivery to the application area (Jones 2014). The costs range from 2 USD tCO_2^{-1} for fertilisation with iron (Boyd 2008; Denman 2008) to 457 USD tCO_2^{-1} for nitrate (Harrison 2013). A detailed economic analysis for macronutrient application reports 20 USD tCO_2^{-1} (Jones 2014), whereas (Harrison 2013) details that costs are much higher due to the overestimation of sequestration capacity and underestimation of logistics costs. Cost of ocean fertilisation method ranges are between 50–500 USD tCO_2^{-1} (Minx et al. 2018). Development of new commodity markets based on algae could potentially make CDR commercially profitable.

Techno-economic assessments of ocean alkalinity largely focus on deriving overall energy and carbon balances and there has been little optimisation or comprehensive life cycle assessment. Cost ranges are between 40–260 USD tCO_2^{-1} (Fuss et al. 2018). Accounting for carbon and energy balances across various process life cycles, adding lime (or other reactive calcium or magnesium oxide/hydroxides) to the ocean would cost between 64–260 USD tCO_2^{-1} (Renforth et al. 2013; Renforth & Kruger 2013; Caserini et al. 2019). Rau (2008) and Rau et al. (2018) estimate that electrochemical processes for increasing ocean alkalinity may have a net cost of 3–160 USD tCO_2^{-1}, largely depending on energy cost and co-product (H_2) market value.

Status, costs, potentials, risk and impacts, co-benefits, trade-offs and spill over effects and the role in mitigation pathways of ocean-based approaches are summarised in Table 12.6.

12.3.2.4 Feasibility assessment

Following the framework presented in Chapter 6, a multi-dimensional feasibility assessment on the CDR options covered here is provided in Table 12.5, taking into account the assessment presented in this section. Both DACCS and EW perform positively on the geophysical and technological dimensions. There is limited evidence to assess social-cultural, environmental/ecological, and institutional dimensions as the literature is still nascent for both options. On the economic dimension, the cost is assessed negatively.

Table 12.5 Feasibility assessment of DACCS and EW. The line of sight with references underlying this assessment is provided in Supplementary Material 12.B. Yellow shading signifies the indicator has a positive impact on the feasibility of the option. Light brown shading signifies the indicator has mixed positive and negative effect on the feasibility of the option. Dark brown shading indicates the indicator has a negative impact on the feasibility of the option. NA signifies that the indicator is not applicable for the option, NE indicates no evidence, and LE means limited evidence whether the indicator affects the feasibility of the option. LoA stands for level of agreement; LoE stands for level of evidence, indicated on a scale of 1-5 from low/limited to high/robust.

Mitigation Options	**Direct air carbon capture and storage**		**Enhanced weathering**	
Scenario Results from AR6 database for Paris consistent policies (1.5°C and 2°C): full scenario ensemble if not otherwise specified. Scenario number	***Variable definition***	***Scenarios mean and inter-quartile range***	***Variable definition***	***Scenarios mean and inter-quartile range***

changes by reporting variable				
	DACCS 2050 (Gt)	*0.9 [0.5-1.2]*	***NA***	***NA***
Indicators	**Feasibility barriers or enablers**	**Notes / Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Notes / Role of context, scale, time, temperature goal**
Geophysical dimension				
Physical potential	**LoA=5|LoE=3**	Depends on where DACCS is employed	NA	
Geophysical resources (including geological storage capacity)	**LoA=5|LoE=3**	Depends on where DACCS is employed	**LoA=5|LoE=5**	Silicate rock formations, silicate rock dust stockpiles, C&D waste
Land use	**LoA=5|LoE=4**		**LoA= 5|LoE= 5**	Existing croplands, co-deployable with afforestation/reforestation/BECCS/biochar
Environmental-ecological dimension				
Air pollution	**NE**		**LoA= 2|LoE= 3**	Air-blown rock dust, reduction in NOx emissions
Toxic waste, ecotoxicity and eutrophication	**NE**		**NE**	
Water quantity and quality	**LoA= 3|LoE= 3**	Depends on the technology; some technologies consume water while others generate it	**NE**	
Biodiversity	**NE**		NA	
Technological dimension				
Simplicity	**NE**		**LoA=5|LoE=5**	Straight forward, utilises existing technology
Technology scalability	**LoA= 5|LoE= 4**		**LoA= 4|LoE=4**	Upscaling is potentially straight forward, infrastructure (e.g. road rail) already in place for handling harvests of equivalent mass
Maturity and technology readiness	**LoA= 5|LoE= 3**		**LoA= 5|LoE= 5**	Components of technology are mature, including the application of minerals to land. However, commercially operating supply chains for CO_2 removal are immature, longitudinal field scale demonstrations are required
Economic dimension				
Costs in 2030 and long term	**LoA=2|LoE=2**		**LoA=3|LoE=3**	Developed countries: \$160-190 tCO_2^{-1} removed; developing countries cheaper: \$55-120 tCO_2^{-1} removed

Employment effects and economic growth	**LoA=5|LoE=3**		**NE**	Potential to increase employment in mining, transport sectors
Socio-cultural dimension				
Public acceptance	**LoA=2|LoE=2**	Very few countries examined	LE	US and UK Public support for limited trials with careful monitoring, public concern if it involved opening new mines
Effects on health and wellbeing	**NE**		**NE**	Respirable dust means caution required during application, not a barrier to implementation
Distributional effects	**NE**		LE	Investment incentives for enhanced weathering are potentially broader and include increased yields, improved soils, reduced agrochemical costs, improved runoff water quality in environmentally sensitive areas and potential benefits to marine life
Institutional dimension				
Political acceptance	**NE**		LE	Non-climate co-benefits may be valuable in terms of the policy 'demand pull'
Institutional capacity and governance, cross-sectoral coordination	**NE**		**NE**	
Legal and administrative feasibility	**NE**		**NE**	Probably not limiting for natural silicate rock given existing protocols for fertiliser, potentially limiting for alkaline wastes/by-products

12.3.3 Consideration of options covered in previous sector chapters; A/R, biochar, BECCS, soil carbon sequestration

Status: BECCS, A/R, soil carbon management and biochar are land based options for providing climate mitigation through "negative emissions" (Smith et al. 2016). BECCS (which covers a selection of biomass combustion for electricity production, two biofuel options (bioethanol and Fischer Tropsch diesel from biomass), and bio methane production (through gasification and anaerobic digestion) combines biomass use for energy with CCS to capture and store the biogenic carbon permanently; A/R and soil carbon management involve fixing atmospheric carbon in biomass and soils, and biochar involves converting biomass to biochar and using it as a soil amendment. The total technical and socio-economic potentials for these mitigation options are uncertain, and concerns have been raised about possible adverse side effects on environmental and social sustainability (Smith et al. 2016; Schleicher et al. 2019; Smith et al. 2019c; Hurlbert et al. 2019; Mbow et al. 2019a; Olsson et al. 2019). There also positive side effects which are covered later under co-benefits for BECCS, A/R, soil carbon management and biochar. Negative effects might be avoided and the global potential for cost-effective, negative-emissions biomass energy greatly expanded by considering marine sources of biomass (Hughes et al. 2012).

Among CDR options, BECCS and A/R are most commonly selected by IAMs to meet the requirements of temperature limits of 2°C and below. This is because of relatively lower estimated costs, flexibility, and the fact that IAMs may not have had capacity to model other options. Current IAMs do not represent soil carbon sequestration or biochar. Given the negative emissions potential of soil carbon sequestration and biochar and some potential co-benefits, efforts should be made to include these options within IAMs, so that their potential can be explored further in comparison with other CDR strategies for climate stabilisation, along with possible impacts of bioenergy feedstock production on soil degradation (Smith et al. 2016; Rogelj et al. 2018).

Potential: The technical potential for BECCS is estimated at 0.4–11.30 $GtCO_2$-eq yr^{-1} (Roe et al. 2019). Assessing BECCS deployment in the 2°C pathway, yields about 12 $GtCO_2$-eq yr^{-1} by 2100, which is considered a conservative estimate for BECCS, taking into consideration 1.5°C pathway. The technical potential of 12$GtCO_2$ yr^{-1} in 2100 is the assumption for BECCS absent the use of other CDR technologies (Harper et al. 2018). Potential for 2050 for A/R is given as 0.5–10.12 $GtCO_2$-eq yr^{-1} by full literature (Jia et al. 2019). Potential for Soil carbonisation for 2050 through agroforestry, restoration of degraded land, and conservation agriculture practices is estimated at 0.26–6.78 $GtCO_2$-eq yr^{-1}. Potential for biochar lies between 0.03–6.6 $GtCO_2$-eq yr^{-1}. However, based on a systematic review of the literature, best estimates for sustainable global NET potentials in 2050 are narrowed to 0.5–3.6 $GtCO_2$-eq yr^{-1} for A/R, 0.5–5 $GtCO_2$-eq yr^{-1} for BECCS, 0.5–2 $GtCO_2$-eq yr^{-1} for biochar, 2–4 $GtCO_2$-eq yr^{-1}, and up to 5 $GtCO_2$-eq yr^{-1} for soil carbon sequestration for the 1.5°C scenario due to sustainability concerns (Fuss et al. 2018). The preceding does not consider the expanded BECCS and biochar potentials available through the use of marine biomass for such CDR (Hughes et al. 2012).

Costs: Costs across technologies vary significantly (Smith et al. 2016) and are estimated for BECCS as 15–400 USD tCO_2^{-1}, A/R 0–240 USD tCO_2^{-1}, soil carbon sequestration -45–100 USD tCO_2^{-1} and biochar-10–345 USD tCO_2^{-1}. But according to Fuss et al. (2018), abatement costs for BECCS, A/R, soil carbon sequestration and biochar have been estimated to be between 100–200, 5–50, 0–100, and 30–120 tCO_2-eq^{-1}, respectively corresponding to 2100 potentials.

Risks, impacts, and co-benefits: a brief summary of risks, impacts and co-benefits is provided here since these are covered in Section 12.5. Land-based mitigation competes for land and water, implying possible adverse outcomes for ecosystem health, biodiversity, livelihoods and food security (Smith et al. 2016; Hurlbert et al. 2019; Mbow et al. 2019a) (see Chapter 7). For example, land required for removal of 1.1–3.3 $GtCO_2$ yr^{-1} through afforestation would require an estimated 320 million to 970 million hectares of land (Smith et al. 2016). Nutrient requirements would be substantial at 0.1–1.0 Mt yr^{-1} nitrogen and 0.22–0.99 Mt yr^{-1} of phosphorus. Also soil carbon sequestration has risks related to increased need for addition of nitrogen and phosphorus to maintain stoichiometry of soil organic matter, implying possible losses to water (Fuss et al. 2018). For biochar, risks include possible down-regulation of plant defence genes that may increase plant vulnerability to insects, pathogens, and drought (Fuss et al. 2018).

Possible climate risks relate to direct and/or indirect land carbon losses (A/R, BECCS, biochar), increased N_2O emissions (BECCS, soil carbon sequestration), saturation and non-permanence of carbon storage (A/R, soil carbon sequestration) (Newell and Phylipsen 2018; Smith et al. 2019c; Jia et al. 2019) (see Chapter 7), and potential CO_2 leakage from deep geological reservoirs (BECCS) (see Chapter 6). Concerning permanence of carbon storage, A/R and soil carbon sequestration face risks relating to lack of public acceptance and economic considerations (Newell and Phylipsen 2018). For A/R and BECCS, an associated land cover change may cause albedo changes that reduce mitigation effectiveness (Fuss et al. 2018; Jia et al. 2019). Albedo change can also partly offset the mitigation effect of biochar, although this impact can be minimised by incorporating biochar into the soil (Fuss et al. 2018). In addition, the impact of BECCS on resources, soil health and biodiversity have been identified as important limitations for its projected deployment (Heck et al. 2018; Smith et al. 2016).

Concerning co-benefits, BECCS may contribute to socio-economic-market opportunities, economic diversification, energy independence, and technology development and transfer (Fuss et al. 2018). It may contribute to reduction of other air pollutants, health benefits, and reduced dependency on imported fossil fuels (Newell and Phylipsen 2018). A/R can have co-benefits for employment (caveat: low-paid seasonal jobs) and local livelihoods, can improve biodiversity if native and diverse species are used, and can improve soil carbon, nutrient and water cycling impacts (Fuss et al. 2018). For biochar, co-benefits include increased crop yields and reduced drought impacts, reduced CH_4 and N_2O emissions from soils, and improved soil carbon and nutrient and water cycling impacts (Fuss et al. 2018). Soil carbon sequestration can improve soil quality and resilience and improve agricultural productivity.

Role in Mitigation Pathways: Previous work has suggested that BECCS can play a crucial role in meeting the global climate-change mitigation target, uncertainties remain in two main areas: the availability of biomass, which is affected by many factors including availability of land for biomass production and sustainability of bioenergy (Anandarajah et al. 2018). The significant role of BECCS in meeting the climate goal target has been influenced by the use of IAMs, which only consider BECCS and A/R and use of high discount rates. Inclusion of other CDR options in the scenarios is likely to reduce the value of BECCS in contributing to the target (Köberle 2019).

A/R is the only CDR options to have been deployed commercially and therefore stands a better chance of contribution to future climate mitigation (Roe et al. 2019). For biochar, results indicate that soil carbon sequestration and biochar have useful negative emission potential (each 0.7 GtC-eq yr^{-1}), and that they potentially have lower land impact, water use, nutrient impact, albedo impact and energy requirement and cost, so have fewer disadvantages than some other CDR options. Limitations of soil carbon sequestration as a CDR option centre around issues of sink saturation and reversibility. Biochar could be implemented in combination with bioenergy and BECCS (Smith et al. 2016).

For soil carbon sequestration, integrated assessment models have shown that increasing soil organic carbon sequestration in the agriculture sector could contribute significantly to climate change mitigation and food security (Frank et al. 2017).

Trade off and spill-overs: Some land-based mitigation strategies, such as BECCS and A/R demand land. Combining mitigation strategies has the potential to increase overall carbon sequestration rates (Humpenöder et al. 2014). However, the strategies may also compete for resources (Frank et al. 2017). Land based mitigation strategies currently propose the use of forests (i) as a source of woody biomass for bioenergy and various biomaterials, and (ii) for carbon sequestration in vegetation, soils, and forest products. Forests are therefore required to provide both provisioning (biomass feedstock) and regulating (carbon sequestration) ecosystem services. This multifaceted strategy has the potential to result in trade-offs (Makkonen et al. 2015). Overall, land-based mitigation competes for land with biodiversity. Some land-based mitigation options are incompatible with biodiversity goals, e.g., A/R using monoculture plantations reduces species richness when introduced into (semi-) natural grasslands. Evidence suggests that when mitigation and biodiversity goals are incompatible, biodiversity is typically given a lower priority, especially if the mitigation option is considered risk-free and economically feasible. Approaches that promote synergies, such as sustainable forest management (SFM) reducing deforestation rates, cultivation of perennial crops for bioenergy in sustainable farming practices, and mixed-species forests in A/R, can mitigate biodiversity impacts and even improve ecosystem capacity to support biodiversity while mitigating climate change. Systematic land-use planning would help to achieve land-based mitigation options that also limit trade-offs with biodiversity (Longva et al. 2017).

Status, costs, potentials, risk and impacts, co-benefits, trade-offs and spill over effects and the role in mitigation pathways of afforestation/reforestation, biochar, soil carbon sequestration, peatland and coastal wetland restoration, agroforestry and forest management are summarised in Table 12.6.

Table 12.6 Summary of status, costs, potentials, risk and impacts, co-benefits, trade-offs and spill over effects and the role in mitigation pathways for CDR options

CDR option	**Status (TRL)**	**Cost (USD tCO_2^{-1})**	**Potential (Gt CO_2 yr^{-1})**	**Risk & Impacts**	**Co-benefits**	**Trade-offs and spill over effects**	**Role in mitigation pathways**	**Section**
DACCS	6	60–500	5-40	Energy, water use	Water (solid sorbent DAC designs); can be located anywhere	Water use, energy demand	In a few IAMs; DACCS complements other CDR methods	{12.3.2.1}
Enhanced weathering	3-4	24-578	3.7-95	Mining impacts	Enhanced plant growth, reduced erosion, enhanced soil carbon, reduced pH, soil water retention	Air quality, water quality, energy demand	In a few IAMs; EW complements other CDR method	{12.3.2.2}
Ocean alkalinity enhancement	1-2	40–260	1–100	increase seawater pH and saturation states and may impact marine biota, Emergence of potential toxic species of diatoms stocks	Limiting ocean acidification		No data	{12.3.2.3}
Ocean fertilisation	1-2	50-500	1-3	Other nutrients depletion, plankton death, negative effects on marine life, the likely decadal-scale return to the atmosphere of nearly all the extra carbon removed, risks of unintended side effects	increased productivity and fisheries, reduced upper ocean acidification	subsurface ocean acidification, deoxygenation; altered regional meridional nutrient supply, fundamental alternation of food webs; remove P from the food production system	no data	{12.3.2.3}
"Blue carbon"	2-3	No data	<1	If degraded or lost, coastal blue carbon ecosystems are likely to release most of their carbon back to the atmosphere; potential for sediment contaminants, toxicity, bioaccumulation and biomagnification in organisms; issues related to altering degradability of coastal plants; use of subtidal areas for tidal wetland carbon removal; effect of shoreline modifications on sediment redeposition and natural marsh accretion; abusive use of coastal blue carbon as means to reclaim land for purposes that degrade capacity for carbon removal.	Provide many non-climatic benefits and can contribute to ecosystem-based adaptation, coastal protection, increased biodiversity, reduced upper ocean acidification; could be potentially benefit for human nutrition or as fertiliser in terrestrial agriculture, or as an industrial or materials feedstock		No data	{12.3.2.3}

CDR option	**Status (TRL)**	**Cost (USD tCO_2^{-1})**	**Potential (Gt CO_2 yr^{-1})**	**Risk & Impacts**	**Co-benefits**	**Trade-offs and spill over effects**	**Role in mitigation pathways**	**Section**
BECCS	(5-6)	15-400	0.4-11	Land and water	Reduction of air pollutants and imported fuel and health benefits	Competition for land with biodiversity	Significant contribution from IAMs	Chapter 7, Section 7.4
Afforestation/Reforestation	(8-9)	0-240	0.5-10.5	Land and water	Enhanced employment and local livelihoods, improved biodiversity, soil carbon and nutrient cycling.	Competition for land with biodiversity	Significant contribution from IAMs	Chapter 7, Section 7.4
Biochar	(6-7)	10-345	0.03-6.6	Particulate and GHG emissions from production; biodiversity and carbon stock loss from unsustainable biomass harvest	Increased crop yields and reduced Non-CO_2 emissions from soil; and resilience to drought	Environmental impacts associated particulate matter, competition for biomass resource	In development - not yet in global mitigation pathways simulated by IAMs	Chapter 7, Section 7.4
Soil Carbon Sequestration	(8-9)	45-100	0.26-6.78	Land and water	Improved soil quality, resilience and agricultural productivity.	Attempts to increase carbon sequestration potential at the expense of profitability	In development - not yet in global mitigation pathways simulated by IAMs	Chapter 7, Section 7.4
Peatland and coastal wetland restoration	(8-9)		0.35-1.65	Land and water	Enhanced employment and local livelihoods, increased productivity of fisheries, improved biodiversity, soil carbon and nutrient cycling.		No data	Chapter 7, Section 7.4
Agroforestry	(8-9)		0.11-5.68	Land and water	Enhanced employment and local livelihoods, improved soil quality		No data	Chapter 7, Section 7.4
Forest management	(8-9)		0.44-2.10	Land and water	Enhanced employment and local livelihoods, improved productivity		Contribution from IAMs	Chapter 7, Section 7.4

12.4 Food systems

12.4.1 Introduction

Sufficient food and adequate nutrition are among the fundamental human needs (Ingram 2020; HLPE 2020). Food needs to be grown and processed, transported and distributed, and finally prepared and consumed. Food systems range from traditional, involving only few people and short supply chains, to modern food systems, comprising complex webs of a large number of actors and processes that grow, transform food commodities into food products and distribute them globally (HLPE 2017; Gómez and Ricketts 2013). A 'food system' includes all food chain activities (production, processing, distribution, preparation, consumption of food) and the management of food loss and wastes. It also includes institutions and infrastructures influencing any of these activities, as well as people and systems impacted (FAO 2018a; HLPE 2017). Food choices are determined by the food environment consisting of the "physical, economic, political and socio-cultural context in which consumers engage with the food system to acquire, prepare and consume food" (HLPE 2017). Food system outcomes encompass food and nutrition, productivity, profit and livelihood of food producers and other actors in food value chains, but also social outcomes and the impact on the environment (Zurek et al. 2018).

Though production of total calories is sufficient for the world population, concentrated on few crops (Benton and Bailey 2019), availability and access to food is unequally distributed, and there is a lack of nutrient-dense foods such as fruit and vegetables (Berners-Lee et al. 2018; Kc et al. 2018). In 2019, close to 750 million people were food insecure, estimated 2 billion people lacking adequate access to safe and nutritious food in both quality and quantity (FAO et al. 2020); simultaneously, two billion adults are overweight or obese through inadequate nutrition, with an upward trend globally (FAO et al. 2019). Low intake of fruit and vegetables is further aggravated by high intake rates of refined grains, sugar and sodium overall leading to a high risk of non-communicable diseases such as cardiovascular disease and type 2 diabetes (Willett et al. 2019; GBD 2017 Diet Collaborators et al. 2019; Springmann et al. 2016; Clark et al. 2018, 2019) *(robust evidence, high agreement).* At least 340 million children under 5 years experience lack of vitamins or other essential nutrients, including almost 200 million suffering from stunting, wasting or overweight (UNICEF 2019).

Malnutrition aggravates susceptibility of children to various infectious diseases (Farhadi and Ovchinnikov 2018; França et al. 2009) and infectious diseases can also decrease nutrient uptake thereby promoting malnutrition (Farhadi and Ovchinnikov 2018). Foodborne illnesses through contamination of food with bacteria, viruses, parasites can cause diarrhoea or infections (Abebe et al. 2020; Ricci et al. 2017; Gallo et al. 2020), food borne substances such as food additives and specific proteins can cause adverse reactions, and contamination with chemical substances can lead to poisoning or chronic diseases (Gallo et al. 2020). Further health risks from food systems originate from the use of antibiotics mainly in livestock production systems and the occurrence of anti-microbial resistance in pathogens (ECDC et al. 2015; Bennani et al. 2020), or zoonotic diseases such as BSE or COVID-19 (Vågsholm et al. 2020; Gan et al. 2020; Patterson et al. 2020).

Modern food systems are highly consolidated due increased vertical and horizontal integration. (Swinnen and Maertens 2007; Folke et al. 2019). This consolidation has led to uneven concentration of power across the food value chain, with more influence concentrated among few actors in the post-farm gate food supply chain (e.g. large food processors and retailers). While agricultural producers contribute a higher proportion of GHG emissions compared with other actors in the supply chain, they have relatively little power to change the system (see Figure 12.6).

In 2016, the agriculture, fisheries, and forestry sectors employed 27% of working people; employment in these sectors was 3% in developed countries – down from 6% in 1995 – and 67% in developing countries – down from 76% in 1995 (World Bank 2019). Employment in other food system sectors such as the food industry and service sectors as compared to farming differs between food systems and the share of total non-farm food system employment ranges between 10% in traditional food systems (e.g., Sub-Saharan Africa), over 50% in food systems in transition (e.g. Brazil) to high shares in modern food systems (e.g. U.S.), about 80% (Townsend et al. 2017).

The IPCC SRCCL estimated overall global anthropogenic emissions from the food systems to range between 10.8 and 19.1 $GtCO_2$-eq yr^{-1}, equivalent to 21–37% of total anthropogenic emissions (Mbow et al. 2019b; Rosenzweig et al. 2020a). The food system approach taken in the IPCC SRCCL Food Security chapter evaluates the synergies and eventual side-effects of food system response options and its implications in food security, climate change adaptation and mitigation. This more integrated framework allows identifying fundamental attributes of responses to maximise synergies, while avoiding maladaptation measures and adverse side effects. A food system approach allows designing more interconnected climate policy responses to tackle climate change from producer and consumer lens. The SRCCL (Mbow et al. 2019b) found that the technical mitigation potential supply- and demand-side responses are fairly comparable and equivalent to 3.0–17.6 $GtCO_2$eq yr^{-1}. This shows that mitigation actions need to go beyond food producers and suppliers to incorporate dietary changes and consumers' behavioural patterns and reveals that producers and consumers need to work hand-in-hand to reduce GHG emissions.

This section complements Chapter 7 assessing mitigation options and instruments until the farm gate by reviewing recent estimates of food system emissions and assessing options to mitigate food systems GHG emissions. Beside major knowledge gaps in the quantification of food system GHG emissions (see Section 12.4.2), the IPCC SRCCL Food Security chapter identified as major knowledge gaps the understanding of the dynamics of dietary change (including behavioural patterns, the adoption of plant-based dietary patterns, and interaction with human health and nutrition of healthy and sustainable diets and associated feedbacks); and instruments and mechanisms to accelerate transitions towards sustainable and healthy food systems.

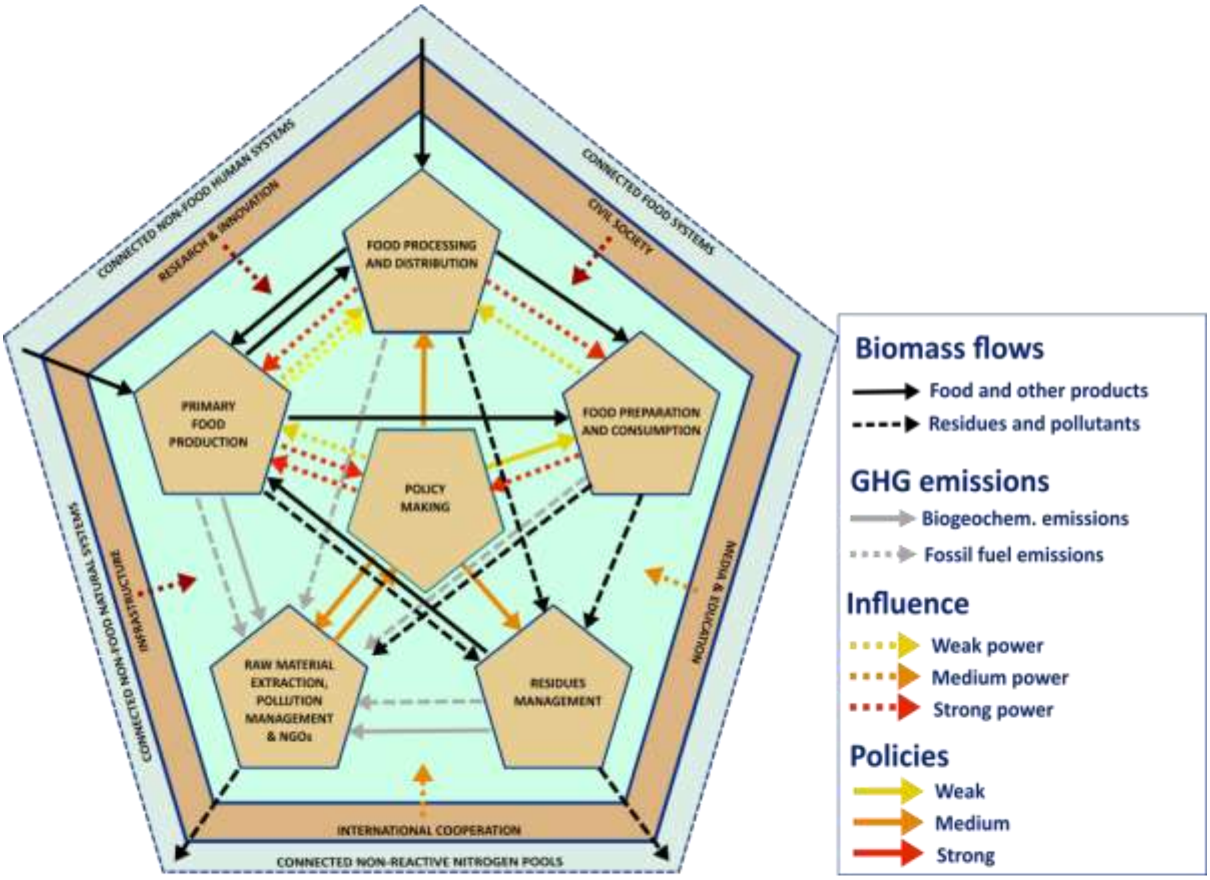


Figure 12.6 Schematic representation of the current global food system, showing sources of GHG emissions from biogeochemical processes and energy consumption, distribution of influences between actors carrying out food system functions, and influence of policy making. Food system actors include people working in the food supply chain, in the management of residues, the extraction of raw materials and the management of environmental losses, as well as citizen consuming the food; other societal groups that can enable or constrain food system transformation: policy makers, research and innovation, service providers, civil society; and media and education. The outer pentagon shows connected food and non-food systems, such as the energy system. The black arrows show flows of biomass as food and other products (intended flows, solid lines) or as residues (dotted lines). Grey arrows indicate emissions from biogeochemical processes (solid lines) or from fossil fuels (dotted lines). The dotted red arrows indicate the influence that food system actors exert on other food system actors in the current global food system.

12.4.2 GHG emissions from food systems

12.4.2.1 Sectorial contribution of GHG emissions from food systems

The IPCC SRCCL Food Security identified major knowledge gaps for the GHG emission inventories of food systems, particularly in providing disaggregated emissions from food industry and transportation. New calculations with EDGAR and FAO data bases (Crippa et al. 2019) have shown that, in 2015, 18.0 Gt CO_2eq yr^{-1} (95% confidence range 14-22 Gt CO_2eq yr^{-1}) were associated with the production, processing, distribution, consumption of food or management of food system residues, corresponding to 34% of total anthropogenic GHG emissions of 53.7 Gt CO_2eq yr^{-1} (range 25%-42%). The largest contribution of food systems GHG emissions was from agriculture (6.0 Gt CO_2eq yr^{-1}, range 2.1 – 10.8) (see Chapter 7). Emissions from land use and land use change associated to agriculture were 5.7 Gt CO_2eq yr^{-1} (2.9 – 8.5), energy use 3.8 Gt CO_2eq yr^{-1} (3.5 – 4.2), waste management 1.7 Gt CO_2eq yr^{-1} (0.9-2.6), and industrial processes and product use 0.7 Gt CO_2eq yr^{-1} (0.5-0.9).

Energy. Emissions from energy use occurred throughout the food supply chain, with contributions from the manufacturing and construction sectors (900 $MtCO_2$-eq yr^{-1}, out of which 28% was attributable to the food, beverage and tobacco industry) and the transport sector (750 $MtCO_2$-eq yr^{-1}). Energy industries supplying electricity and heat contributed 440 $MtCO_2$-eq yr^{-1}, fuel combustion in agriculture, forestry and fisheries amounted to 400 $MtCO_2$-eq yr^{-1}, emissions from residential and commercial fuel combustion contributed 230 $MtCO_2$-eq $yr^{-1}$and 120 $MtCO_2$-eq yr^{-1}, respectively. 320 $MtCO_2$-eq yr^{-1} were from other sectors.

Refrigeration uses an estimated 43% of energy in the retail / supermarket sector (Behfar et al. 2018) and significantly increases the fuel consumption during distribution. Besides being energy intensive, supermarket refrigeration also contributes to GHG emissions through leakage of substitutes for ozone-depleting substances, though their contribution to food system GHG emissions is estimated to be minor (Crippa et al. 2019). The cold chain accounts for approximately 1% of global GHG emissions – however as the number of refrigerators per capita in developing countries is about one order of magnitude lower than the number in developed countries, the importance of refrigeration to total GHG emissions is expected to increase (James and James 2010). Although refrigeration gives rise to GHG emissions, both household refrigeration and effective cold chains can contributes to a substantial reduction of losses of perishable food and thus in emissions associated with food provision (James and James 2010; University of Birmingham 2018). A trade-off exists between reducing food waste and increased refrigeration emissions, with the benefits depending on type of produce, location and technologies used (Wu et al. 2019; Sustainable Cooling for All 2018).

Transport has overall a minor importance for food system GHG emissions with a share of 6.0–6.3% (Poore and Nemecek 2018; Crippa et al. 2019). The largest contributor to food system transport GHG emissions was road transport (93%), followed by navigation (4.0%), rail (2.3%), and aviation (0.6%). Shipping by air or road consumes one order of magnitude higher energy (road: 70–80 MJ t^{-1} km^{-1} ; aviation: 100-200 MJ t^{-1} km^{-1}) than marine shipping (10–20 MJ t^{-1} km^{-1}) or shipping by rail 8–10 MJ t^{-1} km^{-1}) (FAO 2011). For specific food products with high water content, relatively low agricultural emissions and high average transport distances, the share of transport in total GHG emissions can be over 40% (e.g. bananas, with total global average GHG emissions of 0.7 kg CO_2eq kg^{-1}, (Poore and Nemecek 2018), but it is a minor source of GHG emissions for most food products (Poore and Nemecek 2018).

Industry. Direct industrial emissions associated with food systems are generated by the fertiliser industry for ammonia production (280 $MtCO_2$-eq yr^{-1}) and the refrigerants industry (410 $MtCO_2$-eq yr^{-1}). High emissions come also from the packaging industry, dominated by glass and aluminium production (620 $MtCO_2$-eq yr^{-1}), followed by pulp and paper (62 $MtCO_2$-eq yr^{-1}), with smaller contribution from the metal industry (10 $MtCO_2$-eq yr^{-1}).

Packaging contributed to food system GHG emissions with about 5.4% of total emissions (0.98 Gt CO_2eq yr^{-1} (0.9-1.1). Major emissions come from the use of pulp and paper, aluminium, ferrous metals, and glass, while plastics have only minor contribution to food system GHG emissions. High shares of emissions from packaging are found for beverages and some fruit and vegetables (Poore and Nemecek 2018).

Waste. Management of waste generated in food system (including food waste, wastewater, packaging waste etc.) contributed 1.7 $GtCO_2$-eq yr^{-1} to food systems' GHG emissions, 52% from domestic and commercial wastewater, 40% from solid waste management, and 6.9% from industrial wastewater. Emissions from waste incineration and other waste management systems contribute 1.1%.

Table 12.7 GHG emissions from food systems by sector according to IPCC classification in Mt gas yr^{-1} and share of food systems' GHG emissions to total anthropogenic GHG emissions in 1990 and 2015.

Sector	CO_2	CH_4	N_2O	F-gases	GHG	CO_2	CH_4	N_2O	F-gases	GHG
	Emissions (Mt gas yr-1)					Share of total sectoral emissions (%)				
1990										
1 Energy	2193	11	0	-	2593	10.5%	10.7%	43.9%	-	10.7%
2 Industrial Processes	190	0	0	0	261	14.5%	0%	38.2%	0.1%	14.3%
3 Solvent and Other Product Use	0	-	-	-	0	0.2%	-	-	-	0.2%
4 Agriculture	84	142	5	-	5305	100%	100%	100%	-	100%
5 Land-Use Change & Forestry	6796	2	0	-	6851	165%	100%	100%	-	164%
6 Waste	2	43	0	-	1282	24.3%	71.2%	98.9%	-	72.1%
Total	**9266**	**198**	**6**	**0**	**16291**	**34.6%**	**63.8%**	**80.2%**	**0.1%**	**43.3%**
2015										
1 Energy	3367	12	0	-	3815	10.2%	9.3%	39.7%	-	10.3%
2 Industrial Processes	242	0	0	403	701	7.9%	0.1%	30.3%	44%	16.7%
3 Solvent and Other Product Use	6	-	-	-	6	3.6%	-	-	-	3.2%
4 Agriculture	110	157	6	-	6044	100%	100%	100%	-	100%
5 Land-Use Change & Forestry	5671	1	0	-	5695	148%	100%	100%	-	148%
6 Waste	3	58	0	-	1741	26.5%	73.2%	99.1%	-	74.1%
Total	**9400**	**228**	**7**	**403**	**18003**	**23.4%**	**61.6%**	**78.8%**	**44%**	**33.5%**

Notes: Agricultural emissions include the emissions from the whole sector; biomass production for non-food use currently not differentiated. Non-food system AFOLU emissions are a carbon sink, therefore the share of AFOLU food system emissions is > 100%. Source: EDGARv5 (Crippa et al. 2019) (Crippa et al. 2021, submitted), and FAOSTAT.

12.4.2.2 GHG intensities of food commodities

Despite large variability of GHG footprints across existing production systems, attributional GHG footprints intensities (measured in CO_2-equivalents per kg of product) are highest for ruminant meat and certain crustacean species (e.g. trawled lobster, farmed shrimp and prawn) (Holst et al. 2014; Clune et al. 2017; Hilborn et al. 2018; Tilman and Clark 2014; Clark and Tilman 2017; Nijdam et al. 2012; Poore and Nemecek 2018) *(robust evidence, high agreement).* GHG emissions from beef production are highly variable across production systems (18–210 kgCO$_2$-eq (kg meat)$^{-1}$ [1](Poore and Nemecek 2018, see also Chapter 7), but are generally higher than emissions of pork (7.4–22 kgCO$_2$-eq (kg meat)$^{-1}$) and poultry meat 4.2–20 kgCO$_2$-eq (kg meat)$^{-1}$ and farmed fish (6–27 kgCO$_2$-eq (kg meat)$^{-1}$ (Poore and Nemecek 2018) *(robust evidence, high agreement)*. In traditional production systems, livestock serve multiple functions and are used e.g. for manual work or as an investment good, and can constitute an important source of nutrients as a consumption good (Hetherington et al. 2017). Plant based foods have a significantly lower GHG footprint, unless associated with emissions from land use change, as for example palm and soya oil, coffee and soy (Poore and Nemecek 2018), though per serving GHG

FOOTNOTE: [1] Range from 10th and 90th percentile, values in kg CO$_2$-equivalents per kg of product in retail (Poore and Nemecek 2018) footprints remain lower than those of animal source foods (Kim et al. 2019) *(robust evidence, high agreement)*. For permanent crops such as nuts and citrus, land use change can contribute to carbon sequestration, while for cocoa both sequestration and high emissions from land use change have been observed (Poore and Nemecek 2018). At the same time, plant-based alternatives to meat and other livestock products are being developed (see below). Their increasing visibility in the supermarkets and catering services, as well as the falling production price could make meat substitutes competitive in the timeframe of one to two decades (Gerhardt et al. 2019), which makes predictions on implications for GHG emissions from diet shifts highly uncertain.

Table 12.8 Ranges of GHG intensities [kg CO_2-eq (100 g of protein)$^{-1}$, 10th-90th percentile] in food products with high protein content (Poore and Nemecek 2018)

Protein rich food	10th percentile	90th percentile
Bovine Meat (beef herd)	20	105
Bovine Meat (dairy herd)	9.1	26
Lamb & Mutton	12	27
Milk	5.2	15
Pig Meat	4.6	14
Fish (farmed)	2.5	12
Poultry Meat	2.4	12
Eggs	2.6	7.6
Tofu	1	3.5
Other Pulses	0.46	1.8
Nuts	-2.2*	2.4
Groundnuts	0.62	2.2
Soymilk	0.58	1.5
Peas	0.25	0.75
Grains$$	0.31	1.4

Aggregation of CO_2, CH_4, and N_2O emissions in (Poore and Nemecek 2018) done using IPCC-AR5 100-year factors with climate-carbon feedbacks.

*Conversion of arable to permanent crops can lead to carbon sequestration,

$$ Grains weighted average of wheat, maize, oats and rice by protein intake (FAO Global Food Balance Sheet) based on data provided by (Poore and Nemecek 2018)

12.4.2.3 GHG intensities of food systems

Food systems are connected to other societal systems, such as the energy system, financial system, transport system (Leip et al.). Also, food systems are dynamic and continuously changing and adapting to existing and anticipated future conditions. Food production system are very diverse and vary by farm size, intensity level, farm specialisation, technological level, production methods (e.g., organic, conventional, etc.) (Herrero et al. 2017; Fanzo 2017; Václavík et al. 2013).

The share of GHG emissions from food system generated outside the agriculture sector has increased over the last decades, from 34% in 1970 over 45% in 2000 to 49% in 2015 (Figure 12.7).

Various frameworks have been proposed to assess sustainability of food systems, including metrics and indicators on environmental, health, economic and equity issues (Béné et al. 2020; Chaudhary et al. 2018; Gustafson et al. 2016; Eme et al. 2019; Hallström et al. 2018; Zurek et al. 2018).

To visualise the GHG intensity of food systems in a GHG context, Figure 12.8 shows the GHG emissions per capita and year for regional country aggregates, plotted with share of GHG emissions from energy use (Crippa et al. 2021) as the y-axis as a GHG relevant proxy for food system type (see also Section 12.4.1) versus the household expenditure on food (Springmann et al.) as proxy for access to (healthy) food (Chen et al. 2016; HLPE 2020; Hirvonen et al. 2019; Finaret and Masters 2019; Springmann et al.).

Adequacy of the diet with respect to nutritional adequacy and balance, avoidance of food insecurity, over-, or mal-nutrition and associated non communicable diseases (Stanaway et al. 2018; GBD 2017 Diet Collaborators et al. 2019) is indicated by the share of deaths attributed to one of the following risk factors: Child and maternal malnutrition (red), Dietary risks (yellow) or High body-mass index (blue).

While total food system emissions in 2015 range from 0.4–5.2 tCO_2-eq cap^{-1} yr^{-1} across countries, the share of energy emissions relative to energy and land-based (agriculture and food system land use change) emissions ranges between 38% and 99%. Expenditures for food range 3.9–14 USD cap^{-1} day^{-1}, though there is high variability within countries and the cost of nutrient adequate diets often exceeding those of diet delivering adequate energy (Bai et al. 2020; Hirvonen et al. 2019; FAO et al. 2020) and low-income households affected by food insecurity also affected in industrialised countries (Penne and Goedemé 2020).

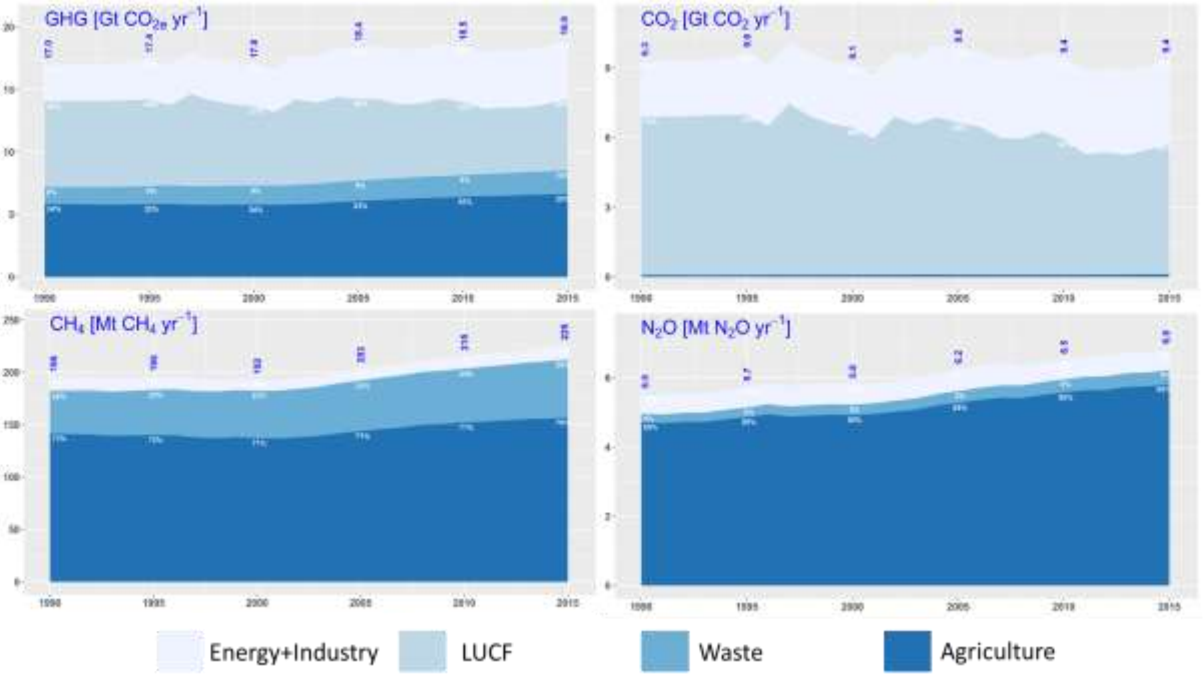


Figure 12.7 Food system GHG emissions from the agriculture, LUCF, Waste, and energy & industry sectors. Data source: (Crippa et al. 2021).

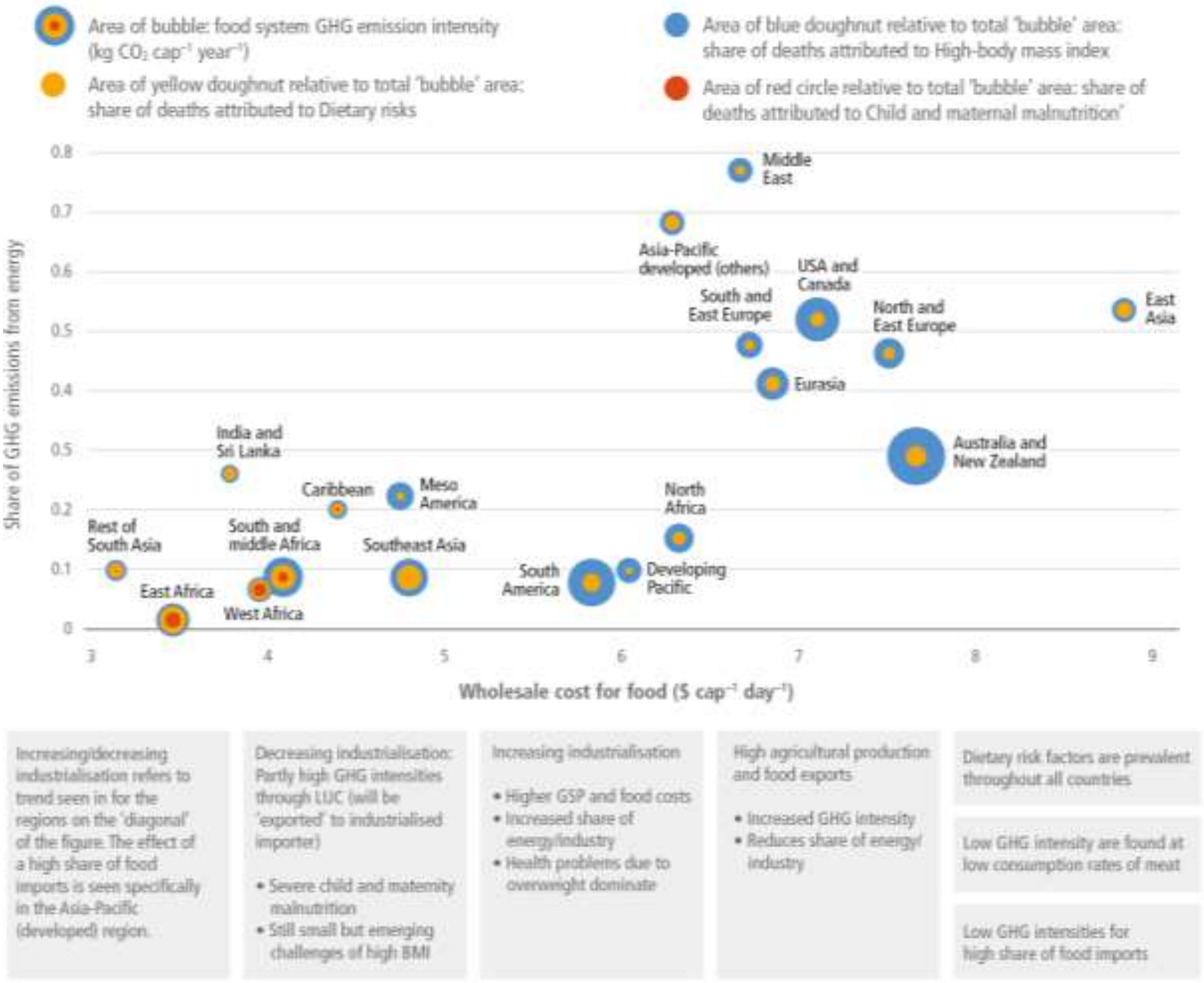


Figure 12.8 Regional differences in health and GHG emissions as outcomes of national food systems. The x-axis shows the cost for food (whole sale price) per capita (Springmann et al., in review); the y-axis shows the ratio of GHG emissions from energy to GHG emissions from energy and land (Crippa et al. 2021). The size of the bubbles shows the total food system GHG emissions in a region per capita and year (Crippa et al. 2021). The sizes of the area of the red, yellow, and blue circles indicates the relative share of deaths attributed to Child and maternal malnutrition (red), Dietary risks (yellow), or High body-mass index (blue) (IHME 2018; GBD 2017 Diet Collaborators et al. 2019). Regional GHG emissions intensities are calculated on the basis of EDGAR data on national GHG emissions.

12.4.3 Mitigation opportunities

Options to reduce GHG emissions from food systems include measures that reduce direct GHG emissions, reduce indirect emissions by reducing energy and/or material demand, by substituting food products with high GHG intensities with others of lower GHG intensities, by reducing food over-consumption or by reducing food loss and waste. The substitution of food products with others that are more sustainable and/or healthier is often called 'dietary shift'. Dietary shift is possible with current technologies and food products (Clark et al. 2020; Jarmul et al. 2020; Willett et al. 2019) but other technologies are proposed to scale-up food products that have currently insignificant share in many countries, or new food products that could help making the dietary shift 'easier' for all citizens. All food supply chain stages can contribute to reduction in food loss and waste, where food losses occur at the farm, post-harvest and food processing/wholesale stages, while in the final retail and consumption stages the term food waste is used (see Section 7.4.5.2 HLPE 2014). Mitigation opportunities through reducing food loss and waste are described for each of these stages, while mitigation opportunities in the waste sector itself is discussed in Chapter 8.

We distinguish food system mitigation opportunities in five different categories as given in Table 12.9:

- Agricultural food production and fisheries (see Chapter 7 and Section 12.4.3.1)
- Controlled environment agriculture (see Section 12.4.3.2)
- Emerging food production technologies (see Section 12.4.3.3)
- Food processing industries (see Section 12.4.3.4)
- Storage and distribution (see Section 12.4.3.5)

Food system mitigation opportunities can be either incremental or transformative (Kugelberg et al. 2021b). Incremental options are based on mature technologies, for which processes and causalities are understood, and their implementation is generally accepted by society. They do not require a substantial change in the way food is produced, processed or consumed and might lead to a (slight) shift in production systems or preferences. Transformative mitigation opportunities have wider food system implications and usually coincide with a significant change in food choices. They are based on technologies that are not yet mature and are expected to require further innovation (Klerkx and Rose 2020), and/or mature technologies that might already be part of some food systems but are not yet widely accepted and have transformative potential if applied at large scale, e.g. consumption of insects or microalgae. Many emerging technologies might be seen as a further step in agronomic development where land-intensive production methods relying on the availability of naturally available nutrients and water are successively replaced with crop variants and cultivation practices reducing these dependencies at the cost of larger energy input (Winiwarter et al. 2014). The effectiveness in climate mitigation is thus inherently linked with increasing energy efficiency and the use of energy from renewable sources. Food system transformation can lead to regime shifts or (fast) disruptions (Pereira et al. 2020) if driven by events that are out of control of private or public measures and have a ‘crisis’ character (e.g. BSE, swine pest).

Table 12.9 summarises the main characteristics of food system mitigation opportunities, their effect on GHG emissions, and main co-benefits and trade-offs.

1 **Table 12.9 Food system mitigation opportunities**

Food system mitigation options		Incremental/Transformative	Direct and indirect GHG effect (+/0/-) [$]	Co-benefits / Adverse effects [&]	Source
Agricultural food production and fisheries	- Digital agriculture	I … T	D+ (improved logistic)	L+ Land sparing R+ Increasing resource use efficiencies	Finger et al. (2019); Herrero et al. (2020)
	- Gene technology	T	D+ (higher productivity)	H+Increase nutritional quality	Steinwand et al. (Steinwand and Ronald 2020); Zhang et al. (Zhang et al. 2020a);Herrero et al. (2020)
	- Sustainable intensification	I	D+ (decreased GHG footprint)	L+ Land sparing R- Some measures might increase the risk of pollution/biodiversity loss	Folberth et al. (2020); Herrero et al. (2020)
	- Agroecology	I	D+ (decreased GHG emissions per area, positive micro-climatic effects); E+ (lower energy inputs, possibly shorter transport distances); FL+ (circular approaches)	+ Focus on co-benefits/ecosystem services R+ Circular approaches increase nutrient and water use efficiencies	HLPE (2019); Wezel et al. (2009); Van Zanten et al. (2019; 2018); van Hal et al. (2019)

Food system mitigation options		Incremental/Transformative	Direct and indirect GHG effect (+/0/-) $	Co-benefits / Adverse effects &	Source
Controlled environment agriculture$	- Soilless agriculture	T	D+ (higher productivity, independent from weather conditions) FL+ (harvest on demand) E- (currently high energy demand, but shorter transport distances, building spaces can be used for renewable energy)	R+ Controlled & closed-loop water and nutrient supply L+ Land sparing H+ Crop breeding can be optimised for taste and/or nutritional quality	Beacham et al. (2019); Benke and Tomkins (2017); Gómez and Gennaro Izzo (2018); Maucieri et al. (2018); Rufí-Salís et al. (2020); Shamshiri et al. (2018)
Emerging Food Production technologies	- Insects	T	D0 (Good feed conversion efficiency, effect depends on substitution effect) FW+ (Can be fed on food waste)	H0 (good nutritional qualities but attention to allergies and food safety issues required)	Fasolin et al. (2019) , Garofalo et al. (2019), Parodi et al. (2018), Reheem et al., (2019), Varelas (2019)
	- Algae and bivalves	I… T	D+ Low GHG footprints	H+ Good nutritional qualities, if care taken for contamination with hazardous substances R+ Biofiltration of nutrient-polluted waters L+ Land sparing A+ Animal welfare	Gentry et al. (2020), Peñalver et al. (2020), Torres-Tiji et al. (2020), Willer and Aldridge (2020)

Food system mitigation options		**Incremental/Transformative**	**Direct and indirect GHG effect (+/0/-) $^{\$}$**	**Co-benefits / Adverse effects $^{\&}$**	**Source**
	- Plant-based protein sources (analogues)	I… T	D+ (no direct emissions from animals, reduced inputs for feed)	A+ Animal welfare L+ Land sparing H+ Potentially reduced risk from zoonotic diseases, pesticides and antibiotics; but higher processing demand	Fresán et al. (2019), Mejija et al. (2019)
	- Cellular agriculture	T	D+ (no direct emissions from animals, high protein conversion efficiency) E- (increased energy need) FLW+ (less food loss & waste as only edible parts are produced)	A+ Animal welfare P+ No emissions of reactive nitrogen or other pollutants H+ Increased food safety for consumption of animal food, potentially reduced risk from zoonotic diseases, pesticides and antibiotics	Parodi et al. (2018); Tuomisto (2019); Thorrez and Vandenburgh (2019); Tuomisto and Teixeira de Mattos (2011); Mattick et al. (2015); Mattick (2018); Souza Filho et al. (2019); Chriki and Hocquette (Chriki and Hocquette 2020)
Food processing and packaging	- Valorisation of by-products, FLW logistics and management	I	M+ Substitution of bio-based materials FL+ Reduction of food losses		Göbel et al. (2015)
	- Food conservation		FW+ Reduction of food waste E0 Additional energy demand but also energy savings possible (e.g. refrigeration, transport)		Silva and Sanjuán (2019) ; FAO (2019)

Food system mitigation options		Incremental/Transformative	Direct and indirect GHG effect (+/0/-) $^{\$}$	Co-benefits / Adverse effects $^{\&}$	Source
	- Smart packaging and other technologies reducing life cycle GHG emissions and/or improving shelf life	I	FW+ Reduction of food waste M0 Additional material demand but also increased material-efficiency E0 Additional energy demand but also energy savings possible	H+ Possibly increased freshness/reduced food safety risks	Molina-Besch et al. (2019); Poyatos-Racionero et al. (2018); Müller and Schmid (2019); Silva and Sanjuán (2019); FAO (2019)
	- Improved energy efficiency in Food processing	I	E+ Energy saving		Niles et al. (2018)
Storage and distribution	- Improved logistics (location, timing, efficiency etc.) in food distribution	I	D+ Reduced transport emissions FL+ Reduced losses in transport FW- Easier access to food could increase food waste		Lindh et al. (Lindh et al. 2016); Molina-Besch et al. (2019); Wohner et al. (2019); Bajželj et al. (2020); FAO (2019)
	- Specific measures to reduce food waste in retail and food catering	I	FW+ E+ Saving of downstream energy demand M+ Saving of downstream material demand		Buisman et al. (2019); Albizzati et al. (2019); Liu et al., (2016)
	- Use of alternative fuels or transport modes	I	D+ Reduced emissions from transport		
	- Improved efficiency in refrigeration, lightening, climatisation	I	E+ Energy saving		Chaomuang et al. (2017); **Lemma** et al. (2014)
	- Replacing refrigerants	I	D+ Reduced emissions from the cold chain		Niles et al. (2018); McLinden et al. (2017); Gullo et al. (2017)

[$] Direct and indirect GHG effects: D – Direct emissions, E – Energy demand, M – Material demand, FL – food losses, FW – food waste; direction of effect on GHG emissions: (+) increase, (0) neutral, (-) decrease.

[&] Co-benefits/Adverse effects: H - health aspects, A - Animal welfare, R - resource use, L - Land demand; (+) co-benefits, (-) adverse effects.

12.4.3.1 Agricultural food production and fisheries

Agricultural food production ranges of a wide range of different systems, from smallholder subsistence farms to large animal production factories, in open spaces, greenhouses, rural areas or urban settings. Fisheries include wild catch and aquaculture. Technological innovations have made food production more efficient since the onset of agriculture (Winiwarter et al. 2014; Herrero et al. 2020). Emerging technologies are discussed in the field of digital agriculture (using advanced sensors, big data), gene technology (crop bio-fortification, genome editing, crop innovations), sustainable intensification (automation of processes, improved inputs, precision agriculture) (Herrero et al. 2020) or development of knowledge-intensive and community agriculture (agro-ecological approaches, urban farms) (HLPE 2019).

Such technologies may contribute to a reduction of GHG emission at the food system level enhanced provision of food, better consideration of ecosystem services, or contribute to nutrition sensitive agriculture, for example, by increasing the nutritional quality of staple crops, increasing the palatability of leguminous crops such as lupines, or the agronomic efficiency or resilience of crops with good nutritional characteristics.

For details on agricultural mitigation opportunities refer to Chapter 7.

12.4.3.2 Controlled environment agriculture

Controlled environment agriculture is mainly based on hydroponic or aquaponics cultivation and is independent from the availability of soil and can therefore largely be termed ‘soil-less food production’. Aquaponics combine hydroponics with a flow-through re-circulating aquaculture compartment for integrated production of plants and fish (Junge et al. 2017; Maucieri et al. 2018), while aeroponics is a further development of hydroponics that replaces water as a growing medium with mist of nutrient solution (Al-Kodmany 2018). Aquaponics could potentially produce proteins in urban farms, but the technology is not yet mature and its economic and environmental performance is unclear (O’Sullivan et al. 2019; Love et al. 2015).

Even though controlled-environmental agriculture per se is not bound to urban environment and installations in rural areas exist, they take often advantage of short supply chains (O’Sullivan et al. 2019); might use dismissed buildings or be integrated in supermarkets, producing for example herbs ‘on demand’.

Optimising growing conditions, hydroponic systems achieve higher yields than un-conditioned agriculture; possibly can further enhanced in CO_2-enriched atmospheres (Armanda et al. 2019; Shamshiri et al. 2018; O’Sullivan et al. 2019). By using existing spaces or using modular systems that can be vertically stacked, this technology minimises land demand, however being energy intensive and requiring large financial investments. So far, only few crops are commercially produced in vertical farms, such as lettuce, and other leafy greens or herbs due their favourable characteristics, vegetables such as tomatoes and eggplants and berries, and also tuber production is possible in aeroponic systems (Benke and Tomkins 2017; Beacham et al. 2019; O’Sullivan et al. 2019; Armanda et al. 2019). Through breeding, other crops can come into reach of commercial feasibility or crops with improved taste or nutritional characteristics can be grown (O’Sullivan et al. 2019).

Photosynthesis is fuelled by artificial light through LEDs or a combination of natural light with LEDs. Control of the wave band and light cycle of the LEDs, micro-climate can be used to optimise photosynthetic activity, yield and crop quality (Gómez and Gennaro Izzo 2018; Shamshiri et al. 2018).

Co-benefits of controlled-environment agriculture include minimising water and nutrient losses as well as agro-chemical use (Farfan et al. 2019; Shamshiri et al. 2018; O’Sullivan et al. 2019; Armanda et al. 2019; Al-Kodmany 2018; Rufí-Salís et al. 2020) *(robust evidence, high agreement)*. Water is recycled in a closed system and additionally some plants generate fresh water by evaporation from grey or black water and high nutrient use efficiencies are possible. Food production from controlled environment agriculture is independent of weather conditions and able to satisfy consumer demand for locally produced fresh and diverse produce throughout the year (O'Sullivan et al. 2019; Al-Kodmany 2018; Benke and Tomkins 2017).

Controlled-environment agriculture is a very energy intensive technology (mainly for cooling) and its GHG intensity depends therefore crucially on the source of the energy. Options for increasing performance and thus reducing GHG intensity of food products include reducing energy need through improved lighting and cooling efficiency, and by employing renewable energy sources, partly integrated into the building structure (Benke and Tomkins 2017).

Comprehensive studies assessing the GHG balance of controlled-environment agriculture are yet lacking. The overall GHG emissions from controlled-environment agriculture is therefore uncertain and depends from the balance of reduced GHG emissions from production and distribution and reduced land requirements, versus increased external energy needs.

12.4.3.3 Emerging foods and production technologies

There is a large number of very diverse emerging food products and production systems that are proposed to reduce GHG emissions from food production, mainly to produce alternative protein sources that can replace conventional animal-source food. An overall assessment of the potential of dietary changes is given in Chapter 7. Here, we assess GHG intensities of emerging food production technologies. This includes products such as insects, algae, mussels, products from bio-refineries which are not 'new' as such, as they are or were already consumed in certain societies and/or in smaller quantities (Souza Filho et al. 2019; Pikaar et al. 2018; Jönsson et al. 2019; Govorushko 2019; Raheem et al. 2019a). The 'new' aspect considered here is rather the scale at which they are discussed and proposed to replace conventional food with the aim to reduce both negative health and environmental impact.

Meat analogues have been able to attract substantial venture capital and were able to substantially decrease production costs in the last decade or even reach market maturity for some products (Mouat and Prince 2018; Santo et al. 2020), but there is uncertainty whether they will 'disrupt' the food market or remain niche products. According to Kumar et al. (2017), the demand for plant-based meat analogues is likely to increase as their production is relatively cheap and they satisfy consumer demands with regard to health and environmental concerns as well as ethical and religious requirements. Consumer acceptance is still low for some options, especially insects (Aiking and de Boer 2019) and cultured meat (Chriki and Hocquette 2020).

Insects. Farmed edible insects have a higher feed conversion ratio than other animals farmed for food, and have short reproduction periods with high biomass production rates (Halloran et al. 2016). Insects have good nutritional qualities (Parodi et al. 2018). They are suited as a protein source for both human and livestock with high protein contents and favourable fatty acid composition (Fasolin et al. 2019; Raheem et al. 2019b). If used as feed, they can grow on food waste and manures. If used as food, food safety concerns/regulations can restrict the use of manure (Raheem et al. 2019b) or food waste (Varelas 2019) as growing substrate and the risk of pathogenic or toxigenic microorganisms or incidences of anti-microbial resistance needs to be confronted (Garofalo et al. 2019).

Algae and bivalves have a high protein content and a favourable nutrient profile and can play a role in providing sustainable food. Bivalves are high in omega-3 fatty acids and vitamin B12 and therefore well suited as replacement of conventional meats with a lower GHG footprint (Willer and Aldridge 2020; Parodi et al. 2018) and micro- and macro algae are rich in omga-3 and omega-6 fatty acids, anti-oxidants and vitamins (Peñalver et al. 2020; Parodi et al. 2018; Torres-Tiji et al. 2020). Algae and bi-valves can be used filter nutrients from nutrient-polluted waters though care is to be taken to avoid accumulation of hazardous substances (Willer and Aldridge 2020; Gentry et al. 2020).

Plant-based meat analogues. Demand for plant-based proteins is increasing and incentivising the development of protein crop varieties with improved agronomic performance and/or nutritional quality (Santo et al. 2020). There is also an emerging market for meat replacements based on plant proteins, such as pulses, cereals, soya, algae and other ingredients mainly used to imitate the taste, texture and nutritional profiles of animal-source food (Kumar et al. 2017). Currently, the majority of plant-based meat analogues is based on soy, while other products still serve a 'niche' market, their share is growing rapidly and some studies project a sizeable share already within a decade (Kumar et al. 2017; Jönsson et al. 2019). In particular plant based milk alternatives have seen large increases in the market share (Jönsson et al. 2019). An LCA analysis of 56 plant based meat analogues showed mean GHG intensities (farm to factory) of 0.21-0.23 kgCO_2-eq per 100 g of product or 20 g of protein for all assessed protein sources (Fresán et al. 2019). Higher footprints were found in the meta-review by Santo et al. (2020; mean 1.8 kgCO2-eq per 100 g of protein). Including preparation, Meija et al. (2019) found higher emissions for burgers and sausages as compared to minced products.

Cellular agriculture. The use of fungi, algae and bacteria is an old process (beer, bread, yoghurt) and serves, among others, also for the conservation of products. The concept of cellular agriculture (Mattick 2018) covers bio-technological processes that use of micro-organisms to produce acellular (fermentation based cellular agriculture) or cellular products. Yeasts, fungi or bacteria can synthesise acellular products such as heme, milk and egg proteins, or protein-rich animal feed, other food ingredients, and pharmaceutical and material products (Rischer et al. 2020). Cellular products include as cell tissues such as muscle cells to grow cultured meat, fish or other cells (Rischer et al. 2020; Post 2012) and products where the micro-organisms will be eaten themselves (Sillman et al. 2019; Pikaar et al. 2018; Schade et al. 2020). Some microbial proteins are produced in a 'reactor' and use Haber-Bosch nitrogen and vegetable sugars or atmospheric CO_2 as source of N and C (Simsa et al. 2019; Pikaar et al. 2018). Cultured meat is currently still in a research stage and some challenges have still to be overcome, such as the need of animal-based ingredients, for example to ensure fast/effective growth of muscle cells to produce cell tissues such as muscle cells to produce cultured meat, and the production at scale and at competitive costs (Post 2012; Rubio et al. 2019; Tuomisto 2019; Stephens et al. 2018; Post et al. 2020). Only few studies so far have quantified the GHG emissions of microbial proteins or cultured meat (Tuomisto and Teixeira de Mattos 2011; Mattick et al. 2015; Souza Filho et al. 2019), suggesting GHG emissions at the level of poultry meat if produced with current energy mix (Tuomisto 2019; Thorrez and Vandenburgh 2019) *(low evidence, low agreement)*, indicating mitigation potential when using low-emissions substrates (Ritala et al. 2017; Parodi et al. 2018).

A review of available LCA studies on different plant-based, animal source and nine 'future food' protein sources (Parodi et al. 2018) concluded that insects, macro-algae, mussels, myco-proteins and cultured meat show similar GHG intensities per unit of protein (mean values ranging 0.3-3.1 kg CO_2eq per 100 g of protein), comparable to milk, eggs, and tuna (mean values ranging 1.2-5.4 kg CO_2eq per 100 g of protein); while *chlorella* and *spirulina* consume more energy per unit of protein and were associated with higher GHG emissions (mean values ranging 11-13 kg CO_2eq per 100 g of protein). As the main source of GHG emissions from insects and cellular agriculture foods is the use of energy, these foods can profit from increased use of renewable energy (Pikaar et al. 2018; Smetana et al. 2015; Parodi et al. 2018).

Future foods offer other benefits such as lower land requirements, controlled systems with reduced losses of water and nutrients, and likely reduced risks from pesticide and antibiotics use and zoonotic diseases, although more research is needed including allergenic effects and possibly reduced protein bioavailability (Stephens et al. 2018; Alexander et al. 2017; Parodi et al. 2018; Santo et al. 2020; Fasolin et al. 2019; Chriki and Hocquette 2020) *(medium evidence, high agreement).*

12.4.3.4 Food processing and packaging

Food processing includes preparation and preservation of fresh commodities (fruit and vegetables, meat, seafood and dairy products), grain milling, production of baked goods, and manufacture of pre-prepared meals. Food processors range from small local operations to large multi-national food producers, producing food for local to global markets.

Food processing technologies tend to optimise nutritional qualities and resource and energy use. Mitigation in food processing largely focuses on reducing food waste and fossil energy usage during the processing itself, as well as in the transport, packaging and storage of food products for distribution and sale (Silva and Sanjuán 2019). Emissions savings through reducing food waste are achieved by both reducing wastage of primary inputs required for food production, or by valorisation of food processing by-products through nutrient recovery or for energy generation or both, thereby reducing emissions from ultimate disposal and contributing to the circular economy (see Sections 12.6.1.2 and 12.5.5.2). No global analyses of the emissions savings potential from the processing step in the value chain could be found.

Reduced food waste during food processing can be achieved by seeking alternative processing routes (Atuonwu et al. 2018), improved communication along the food value chain (Göbel et al. 2015), optimisation of food processing facilities, reducing contamination, and limiting damages and spillage. Optimisation of food packaging also plays an important role in reducing food waste, in that it can extend product shelf life; protect against damage during transport and handling; prevent spoilage; facilitate easy opening and emptying; and communicate storage and preparation information to consumers (Molina-Besch et al. 2019).

Developments in smart packaging are increasingly contributing to reducing food waste along the food value chain. Active packaging increases shelf life through regulating the environment inside the packaging, including oxygen levels, moisture levels and levels of certain chemicals given off as the food ages. Intelligent packaging communicates information on the freshness of the food through indicator labels (Poyatos-Racionero et al. 2018), and data carriers can store information on conditions such as temperature along the entire food chain (Müller and Schmid 2019).

When considering the benefits of different processing or packaging types, these need to be traded off through life cycle assessments (Silva and Sanjuán 2019). Some options such as aluminium, steel and glass require high energy investment in manufacture when producing from primary materials, with significant savings in the energy investment through manufacture from recyclate being possible. However, these materials are inert in landfill. Other packaging options, such as paper and biodegradable packaging, may require a lower energy investment during manufacture, but can generate methane when consigned to anaerobic landfill where there is no methane recovery. Having said that, packaging can account for only 1–12% (typically around 5%) of the GHG emissions in the life cycle of a food packaging system (Wohner et al. 2019; Crippa et al. 2021, see Secton 12.4.2.1), suggesting that its benefits can often outweigh the emissions associated with the packaging itself.

As highlighted previously, the second component of mitigation in food processing relates to reduction in fossil energy use. Opportunities include energy efficiency in processes (also discussed in Chapter 11), the use of heat and electricity from renewable energy sources in processing (see Chapter 6), through off-grid thermal processing (sun drying, food smoking) and improving logistics efficiencies. Energy intensive processes with energy saving potential include milling and refining (oil seeds, corn, sugar), drying, and food safety practices such as sterilisation and pasteurisation (Niles et al. 2018). Food conservation using natural products (natural sugars, natural acids, vegetable oils, salt, brine) can result in energy savings. Packaging also plays a role: reduced transport energy can be achieved through reducing weights of goods that are transported and improving packing densities in transport vehicles (Molina-Besch et al. 2019; Wohner et al. 2019; Lindh et al. 2016). Choice of packaging also determines refrigeration energy requirements during transport and storage.

12.4.3.5 Storage and distribution

Transport mitigation options along the supply chain include improved logistics, the use of alternative fuels and transport modes and distances. Logistics and alternative fuels and transport modes are discussed in Chapter 10. Transport emissions might increase, if expectations on food availability and diversity increased. New technologies that enable food on demand or online food shopping systems might further increase emissions from food transport; however, the consequences are uncertain and might also entail a shift from individual traffic to bulk transport. Also, the impact on food waste is uncertain as more precise delivery option could reduce food waste, but easier access to a wider range of food could also foster over-supply and increase food waste shares. Mitigation opportunities in food transport are inherently linked to decarbonisation of the transport sector (see Chapter 10).

Retail and the food service industry are the main factors shaping the external food environment or 'food entry points'; they are the "physical spaces where food is obtained; the built environment that allows consumers to access these spaces" (HLPE 2017). These industries have significant influence on consumers' choices and can play a role in reducing GHG emissions from food systems. Opportunities are available for optimisation of inventories in response to consumer demands through advanced IT systems (Niles et al. 2018), and for discounting foods close to sell-by dates, which can both serve to reduce food spoilage and wastage (Buisman et al. 2019).

As one of the highest contributors to energy demand at this stage in the food value chain, refrigeration has received a strong focus in mitigation. Efficient refrigeration options include advanced refrigeration temperature control systems, and installation of more efficient refrigerators, air curtains and closed display fridges (Chaomuang et al. 2017). Also related to reducing emissions from cooling and refrigeration is the replacement of hydrofluorocarbons which have very high GWPs with lower GWP alternatives (Niles et al. 2018). The use of propane, isobutane, ammonia, hydrofluoroolefins and CO_2 (refrigerant R744) are among those that are being explored, to varying degrees of success (McLinden et al. 2017).

Energy efficiency alternatives generic to buildings more broadly are also relevant here, including efficient lighting, HVAC systems and building management, with ventilation being a particularly high energy user in retail that warrants attention (Kolokotroni et al. 2015).

In extensive systems in especially developing countries, better infrastructure for transportation and expansion of processing and manufacturing industries can significantly reduce food losses, particularly of highly perishable food (Niles et al. 2018; FAO 2019).

12.4.4 Food system transitions

Many studies on food systems have used SSPs or RCPs or SPAs framework. However, some studies have also developed alternative narratives to depict food system transitions. Under the SSPs scenarios, pathways of diets and food systems are indirectly represented by using the population and the income projections to determine the total and per capita food demand. Increasingly, studies are also applying direct approach on differentiating pathways of diets and food systems considering the narrative of the SSPs scenarios (for the SSP narratives see also Chapter 3, Section 3).

SSP1 considers consumption of healthy diets with limited food waste, a high agricultural productivity, a low growth in food demand, and a moderate international trade (Riahi et al. 2017; Stehfest et al. 2019; Popp et al. 2017; Lassaletta et al. 2019; Fricko et al. 2017). SSP3 describes food systems with a resource intensive consumption, a low agricultural productivity, a high demand for animal products, a high food waste and strongly constrained international trade (Popp et al. 2017; Lassaletta et al. 2019; Stehfest et al. 2019; Fricko et al. 2017). SSP2 considers food systems with a medium growth in food demand, a medium level of meat consumption, moderate international trade, and medium agricultural productivity (Popp et al. 2017; Lassaletta et al. 2019; Stehfest et al. 2019; Fricko et al. 2017). SSP4 considers high inequalities in food systems with high agricultural productivity in industrial farms but low productivity for small-scale farming (Popp et al. 2017; Lassaletta et al. 2019). SSP5 focuses on technological progress driving rapid economic growth due to development of human capital (O'Neill et al. 2014; Kc and Lutz 2014). However, there are inconsistencies among the SSP studies (Van Meijl et al. 2018), mainly on drivers of food demand, assumption of meat consumption, and reduction of food losses and wastes. Due to variation on demographic structure, the global average dietary requirements vary across the SSPs (Hiç et al. 2016). Looking at food security, SSP1, SSP2, and SSP5 are considered as relatively food secure scenarios (Brown et al. 2017). SSP3 and SSP4 are the scenarios with low food security, where mostly poor suffers from food insecurity (Brown et al. 2017).

Many studies have also developed alternative pathways for diets and food systems. For example, studies consider alternative scenarios of diets (Weindl et al. 2017a,b; Bajželj et al. 2014; Springmann et al. 2018a; Damerau et al. 2016; Bodirsky et al. 2020), reduced food waste and closing yield gaps (Pradhan et al. 2014; Bajželj et al. 2014), nitrogen management (Bodirsky et al. 2014), urban and peri-urban agriculture (Kriewald et al. 2019) and different sustainability targets (Henry et al. 2018b). Some studies have also proposed Representative Agricultural Pathways (RAPs) based on RCP-SSP-SPA framework (Wiebe et al. 2015; Antle et al. 2017). Others have identified research priorities or (changes in) legislation needed to better cope with the different alternatives (Mylona et al. 2018). FAO has also proposal three alternative food system scenarios: "business as usual", "towards sustainability", and "stratified societies" (FAO 2018b).

Although many studies represent future pathways of diets and food systems, a holistic and consistent narratives and quantification of the future pathways of diets and food systems is still missing *(robust evidence, high agreement)*. To fill this gap, (Bodirsky, submitted) has proposed five narratives for future diets and food environments, which are consistent with the SSPs. Another gap in the existing studies is the representation of future status of food security. Most studies cover food availability and food accessibility, while utilisation and stability aspects hardly addressed (Dijk 2014).

12.4.5 Enabling food system transformation

Today, policies addressing different food system actors are in most cases not designed and implemented together, but are under different competencies, such as the agriculture policy, food industry, health and food safety policies as well as fiscal policies. This compartmentalisation makes the identification of synergetic and antagonistic effects difficult and bears the risk of failure due to unintended and unanticipated negative impacts on other policy areas and consequently lack of agreement and social acceptance (Mylona et al. 2018; Mausch et al. 2020) (see Section 12.6.2). Also, the currently relatively low consumer awareness of the environmental impact of food choices, and acceptance of novel food technologies and/or behavioural changes must be addressed (Hartmann and Siegrist 2017; Siegrist and Hartmann 2020).

The development of food system policies must therefore have the character of 'transformative' policies where an overall food strategy forms the umbrella and ensures that all societal actors (private organisations, governmental organisation, civil society) are participating in the formulation of the priorities and their ranking.

12.4.5.1 Food system policies

Food system policies must include both supply-side policies and demand-side policies and make use of a basket of available instruments, including administrative, market-based, information, and behavioural policies. All instruments can be both voluntary or mandatory (Temme et al. 2020; Griffiths and West 2015; Latka et al. 2021; Garnett 2011).

Relevant market based instruments include agricultural and fishery policies (see Chapter 7), trade policies, and taxes and subsidies with the intention of improving public health and/or reducing the environmental impact of the food system. So far, environmental food system policies focus on the primary producers where the majority of pollution is happening (Kanter et al. 2020b), often facing difficulties in enforcement (Kanter and Searchinger 2018) and with limited spill-over effects (Kanter et al. 2020a). Agricultural policies have evolved by food security concerns to ensure availability of sufficient calories at affordable prices (Stoll-Kleemann and Schmidt 2017; Benton and Bailey 2019).

We focus here on policies for a shift to more healthy and/or sustainable diets, reduction of over-consumption, or reducing food waste that target food chain actors beyond the farm gate, i.e. food processors, distributors, consumers, and refer for a discussion of policies targeting primary producers to Chapter 7 and Mbow et al. (2019).

Market based instruments.

Taxes and subsidies: Studies have modelled the potential for policies targeting both improved public health and reduction of GHG to generate cost reductions in health care and labour force productivity exceeding the cost of the instruments (Springmann et al. 2017, 2018b, 2016) *(limited evidence, high agreement)* and are legitimated by internalising environmental and social externalities (Hagenaars et al. 2017; Springmann et al. 2018b), whereby taxes applied at consumer level are suggested to be more effective than levying the taxes at production side (Springmann et al. 2017) *(limited evidence, medium agreement).*

Food-based taxes have so far mainly been implemented to reduce problems with non-communicable diseases and focus on sugar intake, in particular contained in sugar-sweetened beverages. Many health-related organisations recommend the introduction of such taxes to improve the nutrition quality of the products marketed and consumers' diets (Park and Yu 2019; Wright et al. 2017), even though the impacts of food taxes are complex due to cross-price effects and supplier reactions (Cornelsen et al. 2015). Measureable effects of subsidies and taxes in improving the dietary behaviour of consumers are seen above 20% increases found to be effective and depend on income group (Niebylski et al. 2015; Mozaffarian et al. 2018; Nakhimovsky et al. 2016; Cornelsen et al. 2015; Hagenaars et al. 2017) (*medium evidence, medium agreement),* even though longer term effects are scarcely studied (Cornelsen et al. 2015) and effects of sugar tax with lower tax rate have been observed for low-income groups (Temme et al. 2020).

Model results show only small consumption shifts for moderate meat price increases; and high price increases are required to reach mitigation targets, even though model predictions become highly uncertain due to lacking observational data (Zech and Schneider 2019; Fellmann et al. 2018; Bonnet et al. 2018; Mazzocchi 2017; Latka et al. 2021).

Unilateral taxes on food with high GHG intensities have been shown to induce increase net export flows which could reduce global prices and increase global demand; indirect effects on GHG emissions therefore could be reduced by up to 70-90% of national mitigation results (Zech and Schneider 2019; Fellmann et al. 2018) *(limited evidence, high agreement).* Global mitigation potential for GHG taxation of food products at 52 USD $kgCO_2$-eq^{-1} has been estimated at 1 $GtCO_2$-eq yr^{-1} (Springmann et al. 2017).

Taxes have the potential to improve the nutritional quality of diets and reduce GHG emissions from food system, but in order to induce change they need to be accompanied by other policies that increase acceptance and elasticity on one hand, and reduce regressive and distributional problems on the other hand (Säll 2018; Henderson et al. 2018; Niebylski et al. 2015; Hagenaars et al. 2017; Wright et al. 2017; Mazzocchi 2017; Springmann et al. 2017; FAO et al. 2020; Penne and Goedemé 2020) *(robust evidence, high agreement).*

Trade: Since the middle of the last century, global trade of agricultural products has contributed to boost productivity, reduce commodity prices, while also incentivising national subsidies for farmers to remain competitive at the global market (Benton and Bailey 2019). Trade liberalisation has been coined as an essential element of sustainable food systems, and trade liberalisation as one element to achieve sustainable development, that can shift pressure to regions were the resources are less scarce. However, Clapp (2017) argues that the main benefit flows to large transnational firms. Benton and Bailey (2019) argue that low food prices contributed to both yield and food waste increases, and to a focus on staple crops to the disadvantage of nutrient dense foods. However, global trade does also contribute to reduce food insecurity and give access to nutrients (Wood et al. 2018; Traverso and Schiavo 2020). The relevance of trade for food security, and adaptation and mitigation of agricultural production has also been discussed in Mbow et al. (2019)

Trade policies can be used to protect national food system measures, such as front-of-package labels, or to impose border taxes on unhealthy products (Thow and Nisbett 2019). For example, the Fiji government implemented in the frame of the Pacific Obesity Prevention in Communities (OPIC) three measures (out of seven proposed) that eliminated import duties on fruits and vegetables, and imposed 15% import duties on unhealthy oils (Latu et al. 2018). Trade agreements have also the potential to undermine national efforts to improve public health (Unar-Munguía et al. 2019). GHG mitigation efforts in food supply chains can be counteracted by GHG leakage, with a general increase of environmental and social impact in developing countries, and a decrease in the developed countries of consumption (Wiedmann and Lenzen 2018; Sandström et al. 2018; Fellmann et al. 2018). The demand for agricultural commodities has also been associated with tropical deforestation, though a robust estimate on the extent of embodied deforestation is not available (Pendrill et al. 2019).

Investment into research & innovation: El Bilali (2019) assessed research gaps in the food system transition literature and finds a need to bridge the disconnection between consumption and food chain and primary production; a step from research based on case studies to comparative studies to enable the assessment of spatial variability and scalability of food system transitions; also the role of private industry and corporate business is scarcely researched, even though they might, and already do, play a major role in the food system transition.

The InterAcademy Partnership assessed how research can contribute in providing the required evidence and opportunities for food system transitions, with a focus on climate change impact and mitigation (IAP 2018). The project built on four regional assessments in Africa (NASAC 2018), Americas (IANAS 2018), Asia (AASSA 2018), and Europe (EASAC 2017). They conclude with five research areas around food systems to better understand: how are sustainable food systems constituted in different contexts and at different scales, how can transition towards sustainable food systems be achieved, and how can success and failure be measured along sustainability dimensions including climate mitigation?

Regulatory and administrative instruments.

Marketing regulations: Currently, 16 countries regulate marketing of unhealthy food to children, mainly on television and schools (Taillie et al. 2019), and many other efforts are ongoing across the globe (European Commission 2019). They aim to encounter the increase in obesity in children and target products high in saturated fats, trans-fatty acids, free sugars and/or salt (WHO 2010) that was endorsed by 192 countries (Kovic et al. 2018). Worldwide, WHO, UNICEF and other organisations call for action to limit marketing of these products to children. Nutrition and health claims for products are used by industry to increase sales, for example in the sport sector or for breakfast cereals. They can be informative, but can also be misleading if misused for promoting unhealthy food (Ghosh and Sen 2019; Sussman et al. 2019; Whalen et al. 2018).

Marketing restrictions have been shown to be effective in reducing the consumption of unhealthy food. If accompanied by sanctions that are enforced by non-compliance (Temme et al. 2020), strong statutory marketing regulations can significantly reduce the exposure of children to junk food as compared to countries with voluntary restrictions (Kovic et al. 2018). Data on implementation or studies on effectiveness on marketing regulations with a broader food sustainability scope are not available. On the other hand, regulation that mobilise private investments into emergent food production technologies can be instrumental in curbing the cost and making them competitive (Bianchi et al. 2018a).

Organisational procurement: Green public procurement is policy that aims both at improving the food environment and create additional demand for sustainable products (as for example organic products, municipality of Copenhagen) or decrease demand for unsustainable products (e.g. Meatless Monday, Norwegian Armed Forces (Milford and Kildal 2019)). To improve dietary choices and depending on the organisational context, organisations can increase the price of unsustainable options while decreasing the price of sustainable ones, or employ information or choice architecture measures (Goggins and Rau 2016; Goggins 2018). Procurement guidelines exist at global, national, organisational or local level (Neto and Gama Caldas 2018; Noonan et al. 2013). Procurement rules on schools or public canteens increase the accessibility of healthy food and can improve dietary behaviour and decrease the purchase of unhealthy food (Cheng et al. 2018; Temme et al. 2020), while effectiveness can be increased, they need to be implemented along with behaviour change strategies.

Food regulations: Novel foods based on insects, microbial proteins or cellular agriculture cannot directly be marketed but must go through an authorisation process to ensure food safety standards. Several countries have ‘novel food’ regulations the conditions under which what foods can be allowed for human consumption. For example, the European Commissions, in its update of the Novel Food Regulation in 2018, includes in its definition of novel food also food from cell cultures, or produced from animals by non-traditional breeding techniques.

For animal product analogues, regulatory pathways and procedures (Stephens et al. 2018) and terminological issues (defining equivalence questions) (Carrenõ and Dolle 2018; Pisanello and Ferraris 2018) need clarification; but also their relation to religious rules (Chriki and Hocquette 2020).

There are only few mandatory food regulations, such as for example the French ban on wasting food approaching best-buy dates, and donating this food to charity organisations instead. In Japan, the Food Waste Recycling Law has set targets for food waste recycling for industries in the food sector that are increasing and for 2020 range between 50% for restaurants and 95% for food manufacturers (Liu et al. 2016).

Voluntary sustainability standards (VSS) are defined either by a public entity or by private organisations to respond to consumers’ demand for social and environmental standards (Fiorini et al. 2019). For firms, getting the certification of a certain scheme can be costly and are generally beard by the producers and/or supply chain players (Fiorini et al. 2019). For examples the Dutch ‚Green Protein Alliance‘ – an alliance of government, industry, NGOs and academia – formulated the goal to shift the ratio of protein consumption from 60% animal source proteins currently to 40% by 2050 (Aiking and de Boer 2020); Cool Food Pledge signatories commit to a reduction of GHG emissions by 25% (Cool Food 2020). The effectiveness of private VSS however is uncertain. Cazzolla Gatti et al. (2019) have investigated the effectiveness of the Roundtable on Sustainable Palm Oil on halting forest loss and habitat degradation in Southeast Asia and concluded that certified productions of palm oil continued to lead to deforestation.

<u>Informative instruments.</u>

Sustainable Food-Based Dietary Guidelines (sFBDGs): National food based dietary guidelines (FBDGs) provide science-based recommendations of food group consumption quantities. They are available for 90 countries globally (Herforth et al. 2019), adapted to national cultural and socio-economic context, and can be used as a benchmark for food formulation standards or public and private food procurement, or to inform the citizen (Bechthold et al. 2018; Temme et al. 2020). Most FBDGs are constructed out of health consideration and only few so are mentioning environmental sustainability aspects (Ahmed et al. 2019; Ritchie et al. 2018; Bechthold et al. 2018).

Despite the fact that 1.5 billion people adhere to a vegetarian diet out of necessity or choice and position statements of nutrition societies point out that vegetarian diets are adequate if well planned, few FBDGs give recommendation at various detail for vegetarian diets (Costa Leite et al. 2020). An increase in consumption of plant based food is a recurring recommendations in FBDGs lowering the share of animal sourced proteins in the diet, though an explicit reduction or limit of animal source proteins is not often included, with the exception of red or processed meat (Temme et al. 2020). To account for changing dietary trends however, FBDGs need to incorporate sustainability aspects (Herforth et al. 2019). A healthy diet respecting planetary boundaries has been proposed by Willett et al. (2019) and is taken as benchmark for 14 global cities that pledged in October 2019 to adhere to this ‘planetary health diet’ (C40 Cities 2019).

Education on food/nutrition and environment: Consumers are reluctant to adopt sustainable diets because of lack of awareness on the consequences of what they eat, but also out of suspicion towards alternatives that are perceived as not ‘natural’ and that seem to be difficult to integrate into their daily dietary habits (Hartmann and Siegrist 2017; McBey et al. 2019; Stephens et al. 2018) or simply by lack of knowledge on how to prepare or eat foods they have not consumed often (Aiking and de Boer 2020; El Bilali 2019; Temme et al. 2020). Often, misconceptions prevail, as for example the belief that packaging or ‘food miles’ are dominating the climate impact of food (Macdiarmid et al. 2016). However, spill over effects can induce sustainable behaviour from ‘entry points’ such as concerns about food waste (El Bilali 2019). Early-life experiences are crucial determinants for adopting healthy and sustainable life styles (McBey et al. 2019; Bascopé et al. 2019) and improved understanding of sustainability aspects in the education of public health practitioners and in university education is proposed (Wegener et al. 2018). Though information and education show little immediate effects (Apostolidis and McLeay 2016), investment into education might lower the barrier for other policies with a more mandatory character to be accepted and effective (McBey et al. 2019; Temme et al. 2020). *(medium evidence, high agreement).*

Food labels: Instruments to improve transparency and information on food sustainability aspects are based on the assumption of the ’rational’ consumer. Information gives the necessary freedom of choice, but also the responsibility to make the ‘right choice’ (Bucher et al. 2016; Kersh 2015). Studies also find a lack of consumer awareness about the link between own food choices and environmental effect (Grebitus et al. 2016; Leach et al. 2016; de Boer and Aiking 2018; Hartmann and Siegrist 2017) and information is required to raise awareness and acceptance of potentially stricter food system policies. Food labels are important instruments to increase transparency and provide information to consumers.

Back-of-package labels usually provide detailed nutritional information (Temple 2019); front-of-package labels instead can also interpret the information (like the traffic light system or the Nutri-Score label (Kanter et al. 2018b), promote a product (like the healthy star rating implemented in Australia and New Zealand), or warn against frequent consumption (like in Finland already in the 1990s, or 2016 in Chile that as first country required ‘high in’ labels to reduce obesity (Corvalán et al. 2019)). Front-of-package labels serve also as an incentive for industry for healthier or more sustainable products, or serve as a marketing strategy (Kanter et al. 2018b; Van Loo et al. 2014; Apostolidis and McLeay 2016). Carbon footprint labels are difficult to understand as they have to translate this information into choice guiding preferences (Hyland et al. 2017), and simple, interpretative summary indicator front-of-package labels (e.g. traffic lights) are more effective than more complex ones (Tørris and Mobekk 2019; Ikonen et al. 2019; Temple 2019; Bauer and Reisch 2019), and let un-informed consumers profit most (*robust evidence, high agreement)*. Reviews find mixed results but overall a positive effectiveness of food labels to improve direct purchasing decisions (Sarink et al. 2016; Anastasiou et al. 2019; Shangguan et al. 2019; Hieke and Harris 2016; Temple 2019), but effective in enhancing the information level thus possible success of other policy instruments (Al-Khudairy et al. 2019; Samant and Seo 2016; Miller et al. 2019; Temple 2019; Apostolidis and McLeay 2016) *(medium evidence, high agreement)*.

Behavioural instruments.

Choice architecture: Information campaigns and education so far were not able to successfully enable long-lasting behavioural change in food choices. Information is more effective if accompanied by reinforcement through structural changes or by changing the food environment that allows the awareness to be put into effect and overcome the intention-behaviour gap (Broers et al. 2017; Bucher et al. 2016; Tørris and Mobekk 2019, see also Chapter 5). Behavioural change strategies have also been shown to improve efficiencies of school food programs (Marcano-Olivier et al. 2020).

Environmental considerations rank behind financial, health, or sensory factors for determining citizens' food choices (Rose 2018; Gustafson et al. 2019; Hartmann and Siegrist 2017; Leach et al. 2016; Neff et al. 2018). There is evidence that choice architecture (nudging) can be effective in influencing purchase decisions, but regulators to not normally explore this option (Broers et al. 2017). Examples of green nudging include changing the default option, enhancing visibility, accessibility of, or exposure to, sustainable products – and reducing visibility and accessibility of un-sustainable products, or increasing the salience of healthy sustainable choices through social norms or food labels (Ferrari et al. 2019; Wilson et al. 2016; Weinrich and Elshiewy 2019; Bucher et al. 2016; Al-Khudairy et al. 2019; Broers et al. 2017; Bauer and Reisch 2019). Even though supermarkets are among the main interface with the consumer (Vecchio and Cavallo 2019), data on nudging interventions to sustainable diets are scarce (Kraak et al. 2017; Ferrari et al. 2019; Al-Khudairy et al. 2019). Available evidence suggests that choice architecture measures are relatively inexpensive and easy to implement (Ferrari et al. 2019; Tørris and Mobekk 2019), they are a preferred solution if a restriction of choices is to be avoided (Kraak et al. 2017; Vecchio and Cavallo 2019; Wilson et al. 2016), and can be effective (Arno and Thomas 2016; Bianchi et al. 2018b; Bucher et al. 2016; Cadario and Chandon 2018) if embedded in a policy packages (Tørris and Mobekk 2019; Wilson et al. 2016) *(medium evidence, high agreement)*.

Choice architecture measures are also facilitated by growing market shares of animal-free protein sources (Slade 2018) taken up by discounter chains and fast food companies, that enhance visibility of new products and eases integration into daily life for all consumers, particularly if sustainable products are similar to the products they substitute (Slade 2018). This effect can be further increased by media and role models (Elgaaied-Gambier et al. 2018).

12.4.5.2 Food system policy packages

Food systems are currently governed by separated policies area that in most countries scarcely interact or cooperate (iPES Food 2019; Termeer et al. 2018). The trends in the global and national food systems towards a globalisation of food supply chains and increasing dominance of supermarkets and large corporate food processors (Andam et al. 2018; Neven and Reardon 2004; Baker and Friel 2016; Dries et al. 2004; Popkin and Reardon 2018; Reardon et al. 2019; Pereira et al. 2020) has led to both environmental and food insecurity and malnutrition problems. Solving these problems requires a transformation of current global and national food systems (Schösler and Boer 2018; McBey et al. 2019; Kugelberg et al. 2021b). This was so far not successful, also due to insufficient coordination between relevant food system policies *(medium evidence, high agreement)*.

Due to the relevance of food systems' outcomes for many policy areas, bearing the risk of unintended consequences, food system governance requires the cooperation of several policy areas, in particular agriculture, nutrition, health, trade, climate, environment policies, and an inclusive and transparent governance structure (Bhunnoo 2019; Diercks et al. 2019; iPES Food 2019; Termeer et al. 2018; Mausch et al. 2020; Kugelberg et al. 2021b). Trade-offs are insufficiently understood (Mausch et al. 2020; Brouwer et al. 2020). Food system strategies are emerging in some countries, but so far appear to lack transformative characteristics (Trevena et al. 2015; Termeer et al. 2018; Kugelberg et al. 2021b). National policies can be complemented – or possibly pioneered – by initiatives at the local level (Aiking and de Boer 2020; Rose 2018) or by creating and learning from strategic niches (El Bilali 2019). For example, the Milan Urban Food Policy Pact (MUFPP), more than 180 global cities committed to improve food system functioning with integrated, locally adapted strategies (Candel 2019). Transformation of food system may come from technological, social or institutional innovations that start as niches but can potentially lead to rapid changes, including of change social conventions (Jasny 2018; Benton and Bailey 2019).

Reduction of meat (and dairy) consumption in affluent countries is the most effective single measure to mitigate GHG emissions with a high potential of co-benefit for environment, health, food security, biodiversity, and animal welfare *(robust evidence, high agreement)*. Dietary changes are relevant for several SDG, foremost SDG2 (zero hunger) and SDG13 (climate action), but also SDG3 (good health and well-being), SDG12 (responsible consumption and production), SDG14 (life below water), SDG15 (life on land), and SDG6 (clean water and sanitation) (Vanham et al. 2019; Campbell et al. 2018; Mbow et al. 2019a) (see Section 12.6).

However, behavioural change towards reduced meat reduction faces barriers both from agricultural producers, and consumers (Milford et al. 2019; Aiking and de Boer 2020; de Boer and Aiking 2018; Apostolidis and McLeay 2016) and requires policy packages that combine informative instruments with behavioural, administrative and/or market-based instruments and are attentive to the needs and engage all food system actors including civil society networks and change the food environment (Stoll-Kleemann and Schmidt 2017; Kraak et al. 2017; iPES Food 2019; Milford et al. 2019; El Bilali 2019; Temme et al. 2020; Cornelsen et al. 2015) *(robust evidence, high agreement)*.

Information and behavioural policy instruments have been shown to have significant but low effect on changing diets *(high evidence, medium agreement)*, but are mutually enforcing and might be essential to lower barriers and increase acceptance of market-based and administrative instrument *(medium evidence, high agreement)* (see Table 12.10).

Table 12.10 Assessment of food system policies targeting (post-farm gate) food chain actors and consumers

	Type Industry	Type Consumer	Level	Environmental effectiveness	Cost	Distributional effect	Transformative potential	Co-benefits$ (+), adverse side-effect (-)	Feasibility	Coordination, coherence and consistency in policy package
Taxes/subsidies on food products	M	M	M, N	moderate	min 20% price increase	regressive	high	- unintended substitution effects	higher acceptance if compensation or hypothecation	high enforcing effect on other food policies
Taxes/subsidies on GHG	M	M	M, N	moderate	min 50-80 USD tCO_2-eq	regressive	high	- unintended substitution effects + high spill-over effect	higher acceptance if compensation or hypothecation	high, enabling effect on other food policies agricultural / fishery policies
Trade	M, A	-	G, M	moderate	complex effects	impacts global distribution	medium	+ encounters leakage effects +/- effects on market structure and jobs	requires changes in existing trade agreements, depending on global relations	protectionist interventions encounter negative side-effects of any intervention with a price effect
Investment into research & innovation	M, A	-	M, N	high long-term potential	medium	no	high + not yet emerging technologies	+ high spill-over effect + converging with digital society (e.g. block chain)	high	can fill targeted gaps for coordinated policy packages (e.g. monitoring methods)
Marketing regulations	A	I	N	low	low	slightly positive	low		medium	can be supportive

Organisational procurement	A	M, I, B	N, L	medium	low	positive	medium	+ can address multiple sustainability goals	high	reaches large share of population, enabling effect on other food policies
Food regulations	A	B	N	medium	low	no	medium		medium	might be necessary to realise innovations; voluntary standards, if effective, can make stricter measures policies
Sustainable food based dietary guidelines	-	I	M, N, L	low	low	no	high	+ explicitly addresses environment and health aspects	high	can serve as benchmark for other policies (labels, food formulation standards, organisational procurement, product-based taxes, ...)
Education on food/nutrition and environment	-	I	N, L	low short-term	variable	might reach higher educated population first	high long-term potential	+ empowering citizen + high spill-over effect if mandatory	low to medium	high, enabling effect on other food policies
Food labels	A	I	M, N, L	low	low	no	high	+ empowering citizen + high spill-over effect if mandatory	high	facilitates standardisation potentially incorporation of other objectives (e.g. animal welfare, ...) increases awareness
Nudges	A	B	N, L	low	low	no	moderate	+ possibly counteracting information deficit in population subgroups	high	high, enabling effect on other food policies
Food policy packages	M, A	M, I, B	N, L	high	reduces cost of un-coordinated interventions	can be controlled	high	+ balanced, addresses multiple sustainability goals	increases acceptance across stakeholders and civil society	requires coordination between policy areas, inclusiveness of stakeholders and civil society, transparent methods and indicators to assess trade-offs and prioritisation between possibly

conflicting objective, monitoring and evaluation against all objectives

Type: E: Market-based instruments, A: Administrative, I: Informative, B: Behavioural

Level: G: global, M: multinational, N: national, L: local

$ Except health as all interventions assumed to address health and climate mitigation

12.5 Land related impacts, risks and opportunities associated with mitigation options

12.5.1 Overview

Chapter 7 covers mitigation in agriculture, forestry and other land use (AFOLU), including future availability of land and biomass resources for mitigation in other sectors. Chapters 6, 9, 10 and 11 cover the use of bioenergy and other biobased products for mitigation in the energy, transport, building and industry sectors. Chapters 3 and 4 cover land and biomass use, primarily in energy applications, in mitigation and development pathways in the near- to mid-term (Chapter 4) and in pathways compatible with long-term goals (Chapter 3). Section 12.5 covers land related impacts, risks and opportunities associated with (i) land-based mitigation options other than those that are inherent in the food system, which are addressed in Section 12.4; and (ii) other mitigation options that are not designated land-based but may still be associated with land occupation and consequent direct/indirect impacts (see Table 12.11 for overview).

The deployment of climate change mitigation options often alters land conditions, water resources and ecosystem capacity to support biodiversity and a range of ecosystem services. Carbon storage in vegetation and soils can increase or decrease, hence impacting the mitigation value positively or negatively. The prioritisation of one land function will to a varying degree influence other functions, often (but not always) in a constraining way (IPCC 2019; IPBES 2019) (r*obust evidence, high agreement*). Thus, there will often be opportunity costs (but sometimes gains) and possibly higher emissions elsewhere.

Impacts, risks and opportunities associated with land-based mitigation options depend on deployment strategy and on context conditions that vary geographically and over time (Doelman et al. 2018; Smith et al. 2019c; Hurlbert et al. 2019; Wu et al. 2020) *(robust evidence, high agreement).* Results and conclusions from individual studies can therefore not easily be generalised. For example, forest management and harvesting regimes around the world will adjust in different ways to a situation where society seeks to meet climate goals. The outcome depends on forest type, climate, forest ownership and the character and product portfolio of the associated forest industry (Lauri et al. 2019; Favero et al. 2020). How forest carbon stocks, biodiversity, hydrology, etc. are affected by changes in forest management and harvesting in turn depends on both management practices and the characteristics of the forest ecosystems (Nieminen et al. 2018; Thom et al. 2018; Erb et al. 2018; Kondo et al. 2018; Tharammal et al. 2019; Griscom et al. 2018; Runting et al. 2019; Eales et al. 2018) The GHG savings achieved from producing and using forest products will in addition depend on the character of existing societal systems, since this determines the product substitution patterns (Leskinen et al. 2018). Beyond climate effects, the scientific literature has limited geographic coverage (confined mainly to Europe and North America) concerning broader sustainable development impacts, and focuses on environmental and economic impacts, mainly related to dedicated agricultural biomass production (Robledo-Abad et al. 2017; Brinkman et al. 2019; Schleicher et al. 2019).

12.5.1.1 Land occupation associated with different mitigation options

As reported in Chapter 3, in pathways limiting warming to 1.5ºC with no or limited overshoot, land use/land cover changes by 2050 relative to 2010 were -6.6 to -4.2 Mkm^2 for pasture; 2.1 to 3.9 Mkm^2 for energy crops; -2.8 to -1 Mkm^2 for all other crops; and -1.4 to 6.3 for forests Mkm^2 (interquartile range, scenario category C1). For context, the total global areas of forests, cropland and pasture (year 2015) are in the SRCCL estimated at about 40 Mkm^2, 15.6 Mkm^2, and 27.3 Mkm^2, respectively (additionally, 21 Mkm^2 of savannahs and shrublands are also used for grazing) (IPCC 2019). The SRCCL reports that conversion of land for A/R and bioenergy crops at the scale commonly found in pathways limiting warming to 1.5°C or 2°C is associated with multiple feasibility and sustainability constraints, including land carbon losses *(high confidence)*. Pathways in which warming exceeds 1.5°C require less land-based mitigation, but the impacts of higher temperatures on regional climate and land, including land degradation, desertification, and food insecurity, become more severe.

Depending on the desired climate outcome, the portfolio of mitigation options chosen, and the policies developed to support their implementation, different land-use pathways can arise with large differences in the projected agricultural and forest area. Some response options can be more effective when applied together (Smith et al. 2019c); for example, dietary change and waste reduction expand the potential to apply land-based options by reducing the land requirement as much as 5.8 Mkm^2 (0.8–2.4 Mkm^2 for dietary change; about 2 Mkm^2 for reduced post-harvest losses, and 1.4 Mkm^2 for reduced food waste) (Smith et al. 2019c). Stronger mitigation action in the near term, including larger emissions reduction and deployment of other CDR options (DACCS, enhanced weathering, ocean-based approaches, see Section 12.3), can reduce the land requirement for land-based mitigation (Obersteiner et al. 2018; van Vuuren et al. 2018).

Global Integrated assessment models (IAMs) provide insights about the roles of land-based mitigation in pathways limiting warming to 1.5°C or 2°C; interaction between land-based and other mitigation options such as variable electricity generation; influence of land-based mitigation on food markets, land use and land carbon; and the role of BECCS vis- à-vis other CDR options. But IAMs do not capture more subtle changes in land management and in the associated industrial/energy systems due to limited representation of land quality and feedstocks/management practices, and of institutions, governance, and local context. (Rose et al. submitted; Daioglou et al. 2019; Wu et al. 2019; Calvin et al submitted) Relatively coarse temporal and spatial resolution of global IAMs make it difficult to represent biomass production integrated with agriculture and forestry, such as in biomass-crop-livestock systems, agroforestry, double-cropping, and biomass extraction associated with silviculture operations and final felling. A/R have generally been modelled as forests managed for carbon sequestration alone, rather than forestry providing both carbon sequestration and biomass supply (Calvin et al submitted). Because IAMs do not include options of biomass production integrated with existing agricultural and forestry systems, they may over-estimate the total additional land area required for biomass production.

Land occupation associated with mitigation options other than A/R and bioenergy is rarely quantified in global scenarios. Among studies available, (Luderer et al. 2019) modelled land occupation and land transformation associated with a range of alternative power system decarbonisation pathways in the context of a global 2°C climate stabilisation effort. On a per-MWh basis, bio-electricity combined with CCS was found to be more than 20 times as land-intensive as hydropower, coal with CCS, or concentrated solar power, which in turn were around five times as land-intensive as wind and solar photovoltaics (PV). A review of studies of power densities confirmed the relatively larger land occupation associated with biopower, although hydropower overlaps with biopower, see Figure 12.9 (van Zalk and Behrens 2018). Note that the comparisons do not reflect that the different options serve different functions in power systems. Reservoir hydropower and biomass based dispatchable power can provide power stability and quality needed in power systems with large amounts of variable electricity generation from wind and solar power plants. Furthermore, the requirements of transport in grids, pipelines etc. differ. For example, electricity from roof-top solar PV can be used in the same location as it is generated.

The character of land occupation – and consequently the associated impacts, covered in next section – varies considerably among mitigation options and also for the same option depending on geographic location, scale, system design and deployment strategy (Ioannidis and Koutsoyiannis 2020; Olsson et al. 2019). Land occupation associated with different mitigation options can be large uniform areas (e.g., large solar farms, reservoir hydropower dams, or tree plantations), or more distributed occupation, such as wind turbines and patches of biomass cultivation integrated with other land uses in heterogeneous landscapes (Jager and Kreig 2018; Englund et al. 2020; Correa et al. 2019; Cacho et al. 2018).

There are also situations where expanding mitigation is decoupled from additional land use. Floating solar PV in hydropower dams (Lee et al. 2020b; Cagle et al. 2020; Haas et al. 2020; Ranjbaran et al. 2019) and the use of agriculture and forestry residues as bioenergy feedstock (Mouratiadou et al. 2020; Spinelli et al. 2019) increase mitigation value from land that is already occupied. Decoupling can also be achieved through increased efficiency in biomass conversion processes, making biomass available for additional production. For example, bioenergy accounts for about 90% of renewable industrial heat consumption, mainly in industries that can use their own biomass waste and residues, such as the pulp and paper industry, food industry, and ethanol production plants (Chapters 6, 11) (IEA 2020c). Improved process efficiencies and the use of on-site waste and residues for meeting internal energy needs reduce the carbon footprint of the biobased products. Surplus heat and electricity can be sold to other users, e.g., district heating systems, and waste and residues can be used to produce fuels such as wood chips and lignin pellets for combined heat and power and hydrotreated vegetable oils for blending with diesel (Chapters 6, 10, 11).

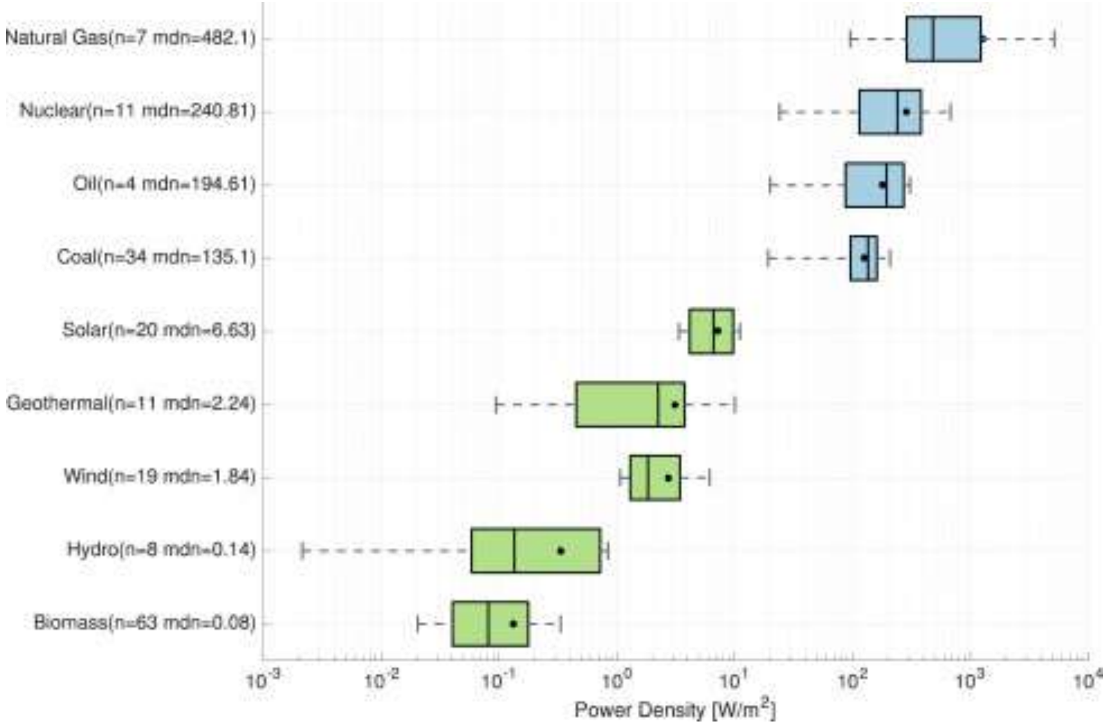


Figure 12.9 Box plots of power densities for different energy options visualised on a log scale. The annotations n and mdn give the number of values found for each energy type, and the median power density respectively. Outliers are those values that are further away than 0.5 and 1.5 times the 1st and 3rd quartiles respectively. The round markers show the mean for each energy type. Green boxes are given for renewable energy types, and blue for non-renewable. Source: (van Zalk and Behrens 2018)

12.5.2 Consequences of land occupation: for land resources and ecosystem services

Mitigation options can present challenges related to impacts and trade-offs associated with land occupation, such as if bioenergy crops, A/R, solar farms or hydropower dams displace natural ecosystems or encroach on land needed for food production and agricultural adaptation to climate change, potentially undermining food security, livelihoods and other aspects of sustainable development. But mitigation options can also provide adaptation opportunities and the deployment of mitigation options can in different ways support the achievement of additional societal objectives. This sub-section covers risks, impacts and opportunities focusing on environment and resources.

Food security is covered in a separate sub-section. In each subsection, we discuss only those mitigation options that have significant risks, impacts and/or co-benefits with respect to that aspect.

12.5.2.1 Risks and impacts, and their mitigation

Land. Mitigation options that are based on the use of land/biomass, that is, bioenergy/BECCS, biochar and other biobased products, can have different – positive and negative – effects depending on the character of the land use/biomass supply system, previous land/biomass use, the biomass conversion process, and how the bio-based products are used. The impacts of the same mitigation option can therefore vary significantly.

There is potential for land degradation through nutrient decline, soil erosion and decline in soil organic matter, due to removal of a higher proportion of above-ground biomass and less protection of the soil surface if forests or grasslands are converted to annual energy crops, or if too much of the crop or forestry residue is extracted from the land (Cherubin et al. 2018). These risks can be reduced or averted by retaining a proportion of the residues to protect the soil surface from erosion and moisture loss, maintain soil organic matter, and by replacing nutrients removed, such as by applying ash from bioenergy combustion plants (Kludze et al. 2013; Harris et al. 2015; Warren Raffa et al. 2015).

Expansion of energy crops, especially monoculture plantations using exotic species, can pose risks to natural ecosystems and biodiversity through introduction of invasive species and land use change, impacting also the mitigation value (Liu et al. 2014; El Akkari et al. 2018). First-generation oil, sugar, and starch crops, tend to have larger negative impact than lignocellulosic crops (Núñez-Regueiro et al. 2020). Selection of energy crops suitable for co-production of protein (e.g., switch grass, reed grass and Miscanthus) can significantly reduce the land conversion pressure by reducing the need to cultivate other crops (e.g., soybean) for protein (Bentsen and Møller 2017; Solati et al. 2018). Biodiversity and ecosystem outcomes can be enhanced through design of energy crop systems (species selection, landscape placement, plantation design and management) (Law et al. 2014; Kavanagh and Stanton 2012; Seddon et al. 2009; Cunningham et al. 2015; Paul et al. 2016; Ferrarini et al. 2017), discussed further in Section 12.5.2.2.

When A/R activities concern the establishment of natural or semi-natural forests, the risk to land is primarily associated with situations where the establishment of tree cover displaces the previous land use to new locations, especially if this indirectly causes deforestation. However, if the forests that become established are managed for production of wood and non-wood forest products, this can reduce deforestation pressure that is caused by demand for such products. In this regard, A/R for the sole purpose of sequestering and storing carbon may be associated with a higher risk of indirect deforestation (ceteris paribus).

The land requirement and impact (including visual impacts) of on-shore wind turbines and solar plants depend on the size and type of installation, and location (Ioannidis and Koutsoyiannis 2020). In the case of wind, only a small percentage of the area occupied is needed for turbine foundations, roads or other infrastructure, and wind power does not crowd out land use activities in the same way as some other mitigation options. Mortality and disturbance risks to bird and bats are major ecological concerns associated with wind farms (Coppes et al. 2020; Choi et al. 2020; Marques et al. 2020; Fernández-Bellon 2020; Thaxter et al. 2017; Cook et al. 2018; Heuck et al. 2019). Painting blades to increase the visibility can reduce mortality due collision (May et al. 2020). Solar thermal and PV power installations can lock away land areas from other uses. However, these use less land per unit of energy output than most other non-fossil options. Land requirement can be reduced through integrating solar thermal and solar PV power systems into buildings and other infrastructure, including hydro dams (see Section 12.5.1.1 and 12.5.3.2). Deserts at low latitudes can be well-suited for solar farms due to high global horizontal irradiance and low competition for land, although remote locations may pose challenges for power distribution.

Establishment of large-scale solar farms could have positive or negative environmental effects, depending on the location of deployment: solar arrays can reduce the albedo, particularly in desert landscapes, which can lead to local temperature increases and regional impacts on wind patterns (Millstein and Menon 2011). Theoretical studies have also suggested that wind turbines could create a local heat island effect due to atmospheric mixing, leading to warmer night temperatures (Keith et al. 2004), later confirmed through observation (Zhou et al. 2013). Recent studies indicate that this warming effect could be substantial with widespread deployment (Miller and Keith 2018a) though (Vautard et al. 2014) found negligible impact at realistic scales of deployment. Modelling studies suggest that large-scale wind and solar farms in the Sahara could increase rainfall through reduced albedo and increased surface roughness, stimulating vegetation growth and further increasing regional rainfall in the Sahel (Li et al. 2018).

Nuclear power has land impacts and risks associated with mining operations, but the land occupation is small compared to many other mitigation options (Figure 12.9). The major issue is associated with the risk that a nuclear accident leads to land contamination due to release of radioactive material. As an example, the 1986 Chernobyl accident in Ukraine resulted in radioactive contamination being spread across Europe. Most of the fallout concentrated near Belarus, Ukraine and Russia, where some 125,000 km^2 of land (more than a third of which was in agricultural use) was contaminated. About 350,000 people were resettled away from these areas, and agricultural products, livestock, and soil were contaminated, making land unusable for humans (Sovacool 2008). About 116,000 people were permanently evacuated from the 4,200 km^2 Chernobyl exclusion zone (IAEA 2006). An example of alternatives to land reclamation for productive purposes, a national biosphere reserve has been established around Chernobyl to conserve, enhance and manage carbon stocks and biodiversity in the Chernobyl exclusion zone (GEF). Long-term empirical data show that the Chernobyl exclusion zone supports an abundant mammal community after nearly three decades of chronic radiation exposures (Deryabina et al. 2015).

Reservoir hydropower projects submerge areas as dams are established for water storage. Hydropower can be associated with significant and highly varying land occupation and carbon footprint (Poff and Schmidt 2016; Scherer and Pfister 2016; Ocko and Hamburg 2019; dos Santos et al. 2017). The flooding of land causes CH_4 emissions due to the anaerobic decomposition of submerged vegetation and there is also a loss of C sequestration by growing vegetation in the flooded area. The size of GHG emissions depends on the amount of vegetation submerged. The carbon in accumulated sediments in reservoirs may be released to the atmosphere as CO_2 and CH_4 upon decommissioning of dams. While uncertain, estimates indicate that these emissions can make up a significant part of the cumulative GHG emissions of hydroelectric power plants (Ocko and Hamburg 2019; Almeida et al. 2019; Moran et al. 2018).

Hydropower projects may impact aquatic ecology and biodiversity, entail the relocation of local communities living within or near the reservoir or construction sites, and can also affect downstream communities (in positive or negative ways) (Moran et al. 2018; Barbarossa et al. 2020). Displacement as well as resettlement schemes can have both socio-economic and environmental consequences including those associated with establishment of new agricultural land. Dam construction also stimulates migration into the affected region, and influxes of people can lead to deforestation and other negative impacts (Chen et al. 2015). Impacts can be mitigated through basin-scale dam planning that considers GHG emissions along with social and ecological effects (Almeida et al. 2019). Land occupation is minimal for run-of-river hydropower installations, but without storage they have no resilience to drought and installations inhibit dispersal and migration of organisms (Lange et al. 2018).

Water. As for impacts on land, the water-related impacts of land-based mitigation options depend on the type of option, where and how it is deployed, and how the land was used previously. Hydropower can have high water usage due to evaporation from dams (Scherer and Pfister, 2016). For bioenergy/BECCS and nuclear power, substantial volumes of water may be required for energy conversion processes (such as for cooling in thermal power plants), but most of this water is returned to rivers and other water bodies after use. Negative impacts on aquatic systems can occur due to chemical and thermal pollution loading. Wastewater treatment can reduce pollution loading and provide mitigation benefits, such as when anaerobic digestion of wastewater reduces methane emissions and produces biogas that can substitute natural gas (Parsaee et al. 2019).

Unlike water used in processing, much of the water used in biomass production systems is transferred to the atmosphere through evapotranspiration and is therefore not available until it returns via precipitation. The deployment of different biomass production systems affects hydrological flows differently. For example, extraction of logging residues in forests managed for timber production has little effect on hydrological flows across larger landscapes, while land use change to establish dedicated biomass production can have a significant effect. Rainfed biomass production does not require water extraction from groundwater, lakes, and rivers, but it can still reduce downstream water availability by redirecting precipitation from runoff and groundwater recharge to crop evapotranspiration, e.g., if deep-rooted perennial plants replace annual crops.

Forests have a large influence the hydrological cycle, from the local to the global level and in varying ways. A/R activities can increase evapotranspiration impacting groundwater and downstream water availability, but can also result in increased infiltration to groundwater and improved water quality (Farley et al. 2005; Lu et al. 2018; Zhang et al. 2016, 2017). While increases in evapotranspiration, through A/R or planting woody crops for energy, can lead to adverse side-effects for agriculture, natural ecosystems and settlements, it can be beneficial where historical clearing has caused soil salinisation and stream salinity (Farrington and Salama 1996; Marcar 2016). Another example of beneficial effects includes perennial grasses planted to intercept runoff and subsurface lateral flow, reducing nitrate entering groundwater and surface waterbodies (e.g Woodbury et al. 2018; Femeena et al. 2018). In India, (Garg et al. 2011) found several desirable effects as a result of planting Jatropha on wastelands previously used for grazing (which could continue in the Jatropha plantations): soil evaporation was reduced, as a larger share of the rainfall was channelled to plant transpiration and groundwater recharge, and less runoff resulted in reduced soil erosion and improved downstream water conditions. Thus, adverse effects are minimised and synergies achieved when plantings are sited carefully, with consideration of hydrological impacts (Davis et al. 2013).

12.5.2.2 Opportunities and their promotion

Integration of perennial plants into agricultural landscapes to enhance, e.g., landscape diversity, habitat quality, retention of nutrients and sediment, erosion control, climate regulation, pollination, pest and disease control, and flood regulation (see Figure 12.10). Such integration can help mitigate impacts from intensive agriculture on land, water and ecosystems. Perennial grasses and woody plants grown for bioenergy or biochar feedstock can be used for such purposes. There is significant experience of this type of biomass production systems from both practical field trials and commercial applications (Asbjornsen et al. 2014; Berndes et al. 2008; Christen and Dalgaard 2013; Dauber and Miyake 2016; Holland et al. 2015; Milner et al. 2016; Ssegane et al. 2015; Ssegane and Negri 2016; Styles et al. 2016; Zalesny et al. 2019).

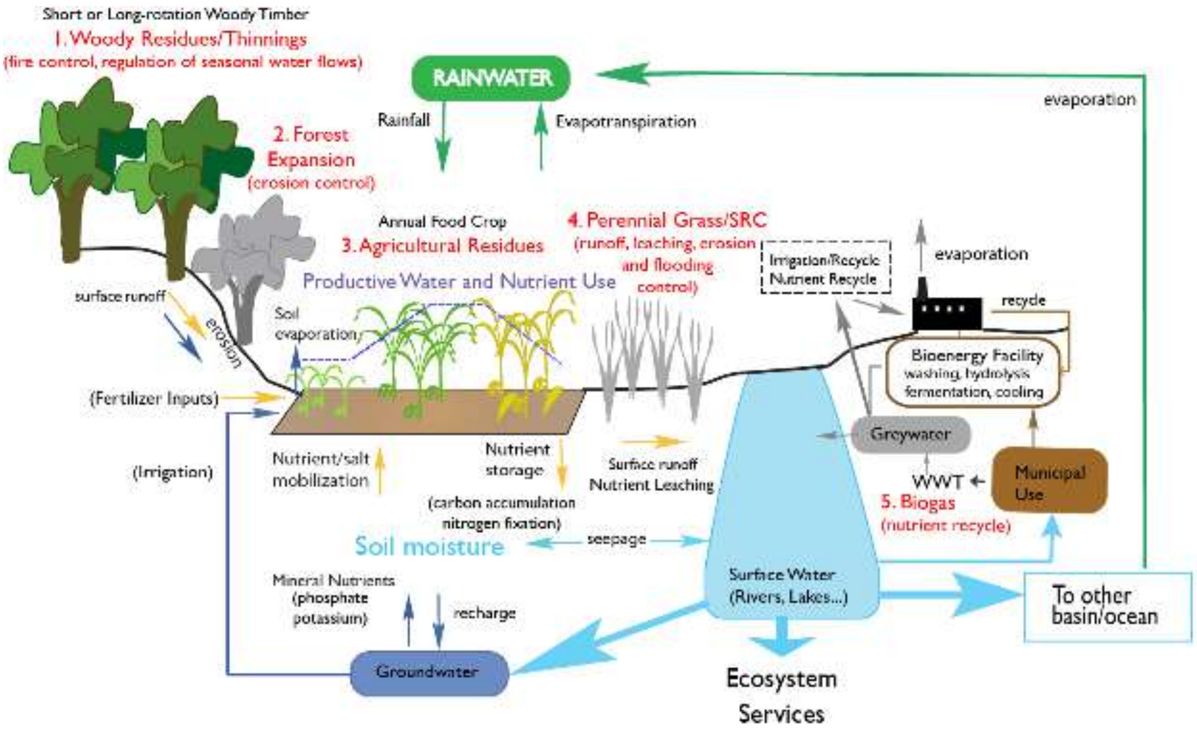


Figure 12.10 Overview of opportunities related to selected land based climate change mitigation options. Source: (Berndes et al. 2015)

Several bioenergy technologies produce non-energy co-products that offer co-benefits for land productivity. Anaerobic digestion can convert organic wastes to biogas and a nutrient-rich digestate (Chapter 6). It can be applied at a range of scales, from household to farm to large facilities, such as sewage treatment plants in large cities. Biogas can be utilised for heating and cooking or be upgraded for use in electricity generation, industrial processes, or as transportation fuel. The digestate is a rich source of nitrogen, phosphorus and other plant nutrients, and its application to farmland returns exported nutrients (Cowie 2020b). Studies have identified potential risks, including Mn toxicity, Cu and Zn contamination, and high ammonia emission potential, compared with application of undigested animal manure (Nkoa 2014) Although the anaerobic digestion process reduces pathogen risk compared with undigested manure feedstocks, it does not destroy all pathogens (Nag et al. 2019). Leakage of methane is a significant risk that needs to be managed, to ensure mitigation potential is achieved (Bruun et al. 2014).

Biorefineries can convert biomass to food, feed and biomaterials along with bioenergy (Aristizábal-Marulanda and Cardona Alzate 2019; Schmidt et al. 2019). Biorefinery plants are commonly characterised by high process integration to achieve high resource use efficiency, minimise waste production and energy requirements, and maintain flexibility towards changing markets for raw materials and products (Schmidt et al. 2019). Emerging technologies can convert biomass that is indigestible for monogastric animals or humans (e.g., algae, grass, clover or alfalfa) into food and feed products. For example, Lactic acid bacteria can facilitate the use of green plant biomass such as grasses and clover into a protein rich fraction suitable for pig feed and other products for material or energy use (Lübeck and Lübeck 2019). Such solutions, using alternatives to high-input, high-emission annual grain and seed crops as feedstock, can enable sustainable intensification of the agricultural systems with reduced environmental impacts (Jørgensen and Lærke 2016). The use of seaweed and algae as biorefinery feedstock can facilitate recirculation of nutrients from waters to agricultural land, thus reducing eutrophication while substituting purpose-grown feed (Makkar et al. 2016; Makkar 2016).

Pyrolysis can convert organic wastes, including food waste, manure, poultry litter and sewage sludge, into combustible gas and biochar, which can be used as a soil amendment. Pyrolysis is well-suited for materials that may be contaminated with pathogens, microplastics or per- and polyfluoroalkyl substances, such as abattoir and sewage wastes, removing these risks and enabling nutrient recovery from these materials by applying biochar to farmland. Conversion to biochar also aids the logistics of transport and application of materials such as sewage sludge. Applying biochar to soil sequesters biochar-carbon and can further increase soil carbon by reducing mineralisation of soil organic matter and newly added plant carbon (Singh et al. 2012; Wang et al. 2016; Weng et al. 2017). Biochars can improve a range of soil properties, but effects vary depending on biochar properties, which are determined by feedstock and production conditions (Singh et al. 2012; Wang et al. 2016a), and on the soil properties where biochar is applied. Biochars can increase nutrient availability and losses (Singh et al. 2010; Haider et al. 2017) and enhance crop yields particularly in infertile acidic soils (Jeffery et al. 2017). Biochars can enhance infiltration and soil water-holding capacity, reducing runoff and leaching, increasing water retention in the landscape and improving drought tolerance and resilience to climate change (Quin et al. 2014; Omondi et al. 2016) (See Chapter 7 for review of biochar's potential contribution to climate change mitigation).

Soil carbon management can simultaneously contribute to climate change mitigation, climate change adaptation and reduced risk of land degradation (IPCC 2019; UN Environment 2019) (*robust evidence, high agreement*). Proven agronomic measures such as cover crops, intercropping, stubble retention and switching from annual to perennial crops or pastures that commonly increase soil carbon stocks can also prevent and reduce soil erosion and nutrient leakage (Culman et al. 2013; Poeplau and Don 2015; Conant et al. 2017; Kaye and Quemada 2017; Sainju et al. 2017; Henry et al. 2018a). Novel perennial grain crops, such as perennial wheat, are anticipated to reduce soil erosion, increase nitrogen retention, have higher water use efficiency and enhance carbon sequestration, compared with annual crops (Crews et al. 2018) but further breeding effort is required to reach acceptable yields.

Avoiding deforestation and forest degradation can help to meet short term climate goals, while sustainable forest management and agroforestry aimed at providing timber, fibre, biomass, non-timber resources and other ecosystem services can provide long-term livelihoods for communities. Sustainable forest management, including agroforestry, can maintain land productivity, thus preventing land degradation, and reducing the propensity for conversion to non-forest uses (e.g., cropland or settlements).

Timber plantations, biomass crops and agroforestry on cleared land can deliver biodiversity benefits (Law et al. 2014; Kavanagh and Stanton 2012; Seddon et al. 2009), with biodiversity outcomes influenced by block size, configuration and species mix (Cunningham et al. 2015; Paul et al. 2016). Re-/afforestation can be undertaken as tree belts placed to create windbreaks that reduce sandstorms and avert desertification. Restoring natural vegetation and establishing plantations in degraded land enable organic matter to accumulate in the soil and have potential to deliver significant co-benefits for biodiversity, land resource condition and livelihoods. Environmental co-benefits are enhanced when ecological restoration principles are applied (Gann et al. 2019). There is some evidence indicating that very large-scale land use / vegetation cover changes can alter regional climate and precipitation patterns, e.g., downwind precipitation depend on upwind evapotranspiration from forests and other vegetation (Ellison et al. 2017; van der Ent and Tuinenburg 2017; Keys et al. 2016).

Mitigation activities can contribute to addressing land degradation through land rehabilitation or restoration (see Box 12.1). Land-based mitigation options that produce biomass for bioenergy/BECCS or biochar through land *rehabilitation* rather than land *restoration* imply a trade-off between production / carbon sequestration and biodiversity outcomes (Cowie et al. 2018; Hua et al. 2016). Restoration, seeking to establish native vegetation with the aim to maximise ecosystem integrity and to conserve on-ground C stock, will have higher biodiversity benefits (Lin et al. 2013), but the sequestered C is vulnerable to loss through disturbance, so there is a higher risk of reversal of the mitigation benefit, compared with use of biomass for substitution of fossil fuels and GHG-intensive building materials (Russell and Kumar 2017; Dugan et al. 2018). Trade-offs between different ecosystem services, and between societal objectives including climate change mitigation and adaptation, can be managed through integrated landscape approaches that aim to create a mosaic of land uses, including conservation, agriculture, forestry and settlements (Freeman et al. 2015; Nielsen 2016; Reed et al. 2016; Sayer et al. 2017) where each is sited with consideration of land potential (Cowie et al. 2018) *(limited evidence, high agreement).*

Solar PV can be deployed in ways that enhance agriculture: for example, (Hassanpour Adeh et al. 2018) found that biomass production and water use efficiency of pasture increased under elevated solar panels. PV systems under development may achieve significant power generation without diminishing agricultural output (Miskin et al. 2019). Agriculture can also coexist in beneficial ways with wind power as the wind power installations occupy a small share of the land within their boundaries and most of the area can be used for other purposes such as grazing and cultivation (Miller and Keith 2018b; Fritsche et al. 2017). Reservoir hydropower schemes can regulate water flows and reduce flood damage to agricultural production (Amjath-Babu et al. 2019).

As many of the SDGs are closely linked to land use, the identification and promotion of mitigation options that rely on land uses described above can support a growing use of biobased products while advancing several SDGs, e.g., SDG2 “Zero hunger”, SDG6 “Clean water and sanitation”, SDG7 “Affordable and Clean Energy” and SDG15 “Life on Land” (Fritsche et al. 2017; IRP 2019). Policies supporting the target of Land Degradation Neutrality (LDN; SDG 15.3) encourage planning of measures to counteract loss of productive land due to unsustainable agricultural practices and land conversion, through sustainable land management, and strategic restoration and rehabilitation of degraded land (Cowie et al. 2018). LDN can thus be an incentive for land-based mitigation measures that build carbon in vegetation and soil, and can provide impetus for land use planning to achieve multifunctional landscapes that integrate land-based mitigation with other land uses (see Box 12.1).

Box 12.1 Land Degradation Neutrality as a framework to manage trade-offs in land-based mitigation

The UNCCD introduced the concept of Land Degradation Neutrality (LDN), defined as “a state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems” (UNCCD 2015), and it has been adopted as a target of Goal 15 of the SDGs, Life on Land. At December 2020, 124 (mostly developing) countries have committed to pursue voluntary LDN targets.

The goal of LDN is to maintain or enhance land-based natural capital, and its associated ecosystem services such as provision of food and regulation of water and climate, while enhancing the resilience of the communities that depend on the land. LDN encourages a dual-pronged approach promoting sustainable land management (SLM) to avoid or reduce land degradation, combined with strategic effort in land restoration and rehabilitation to reverse degradation on degraded lands and thereby deliver the target of “no net loss” of productive land (Orr et al. 2017).

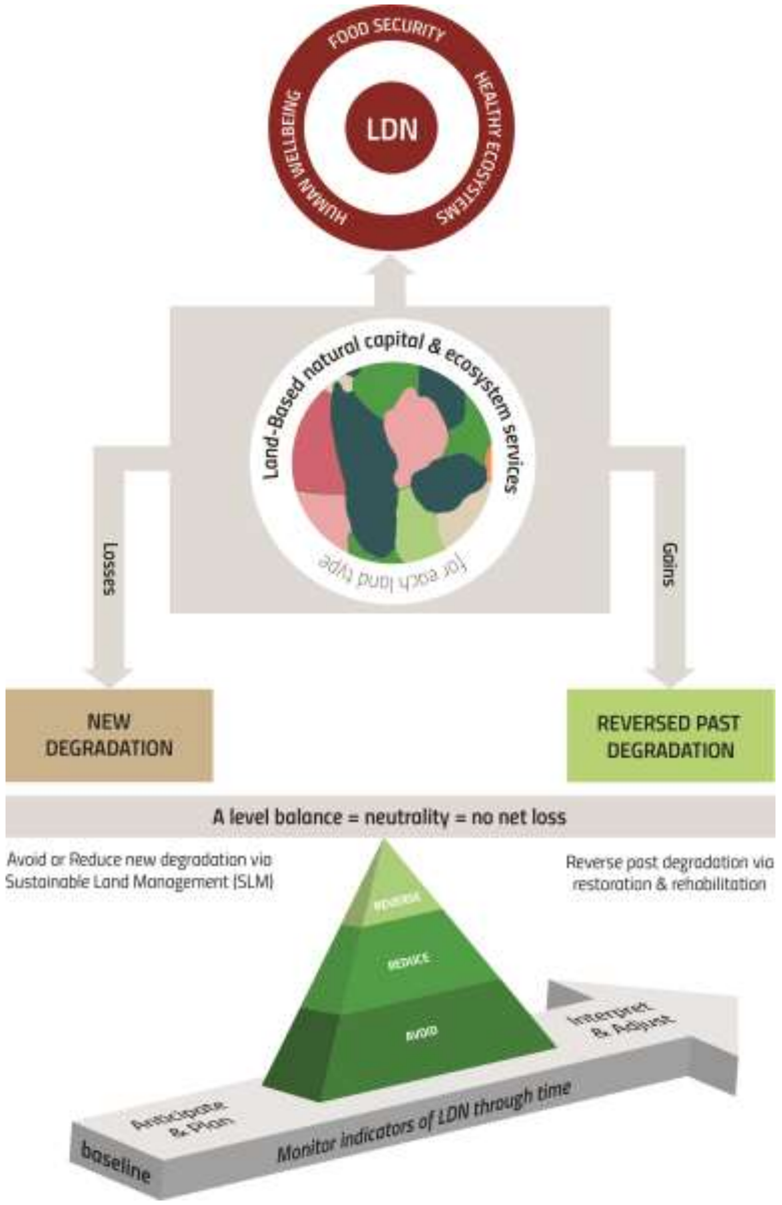
In the context of LDN, land restoration refers to actions undertaken with the aim of reinstating ecosystem functionality, whereas land rehabilitation refers to actions undertaken with a goal of provision of goods and services (Cowie et al. 2018). Restoration interventions can include destocking to encourage regeneration of native vegetation; shelter belts of local species established from seed or seedlings, strategically located to provide wildlife corridors and link habitat; and rewetting drained peatland. "Farmer-managed natural regeneration" is a low-cost approach in which regeneration of tree stumps and roots is encouraged, stabilising soil and enhancing soil nutrients and organic matter levels (Lohbeck et al. 2020). Rehabilitation actions include establishment of energy crops or afforestation with fast-growing exotic trees to sequester carbon or produce timber. Application of biochar can facilitate rehabilitation by enhancing nutrient retention and water holding capacity, and stimulating microbial activity (Cowie 2020a).

SLM, rehabilitation and restoration activities undertaken towards national LDN targets have potential to deliver substantial CDR through carbon sequestration in vegetation and soil. In addition, biomass production – for bioenergy or biochar – could be an economically viable land use option for reversing degradation, through rehabilitation. Alternatively, a focus on ecological restoration (Gann et al. 2019) as the strategy for reversing degradation will deliver greater biodiversity benefits.

Achieving neutrality requires estimating the likely impacts of land-use and land management decisions, to determine the area of land, of each land type, that is likely to be degraded (Orr et al. 2017). This information is used to plan interventions to reverse degradation on an equal area of the same land type. Therefore, pursuit of LDN requires concerted and coordinated efforts to integrate LDN objectives into land-use planning and land management, underpinned by sound understanding of the human-environment system and effective governance mechanisms.

Countries are advised to apply a landscape-scale approach for planning LDN interventions, in which land uses are matched to land potential, and resilience of current and proposed land uses is considered, to ensure that improvement in land condition is likely to be maintained (Cowie 2020a). A participatory approach, enabling effective representation of all stakeholders, is encouraged, recognising that decisions on LDN interventions are likely to involve trade-offs between various environmental and socio-economic objectives.

Planning and implementation of LDN programmes provides a framework in which locally-adapted land-based mitigation options can be integrated with use of land for production, conservation and settlements, in multifunctional landscapes where trade-offs are recognised and managed, and synergistic opportunities are sought. LDN is thus a vehicle to focus collaboration in pursuit of the multiple land-based objectives of the multilateral environmental agreements and the SDGs.



Box 12.1, Figure 1 Schematic illustrating the elements of the Land Degradation Neutrality conceptual framework. Source: (Cowie et al. 2018)

12.5.3 Food security

12.5.3.1 Risks and impacts

The pressure on agricultural land – and the resultant risk to food security – depends on the scale of deployment of land-based mitigation options, the productivity of the land occupied by mitigation measures, and the extent to which mitigation can co-exist with production. This section covers food security impacts and risks that are not associated with mitigation within the food sector itself, as the latter is covered in Section 12.4.

A/R and energy crop production could have adverse impacts on food security if deployed over large total area, in locations that displace food production (IPCC 2019). Some studies may report these measures as associated with a higher risk to food security simply because they are more extensively deployed than, for example, options to reduce grassland conversion to croplands, or restore peatlands or coastal wetlands. But the degree of impact associated with a certain mitigation option also depends on where and how that deployment takes place and also the rate of expansion. If productive cropland is utilised for mitigation measures food security can be impacted, and there is risk of indirect land use change. As an alternative, less-productive land, degraded land, marginal land and abandoned land can be utilised for land-based mitigation with lower impact on food security. (Woods et al. 2015) estimated that 5 million km^2 of abandoned and degraded land is potentially available for energy crops (or re-/afforestation).

However, the identification of such land as "available" has been contested, as much marginal land is used informally by impoverished communities, particularly for grazing, or may be economically infeasible or environmentally undesirable for development of energy crops (Baka 2013, 2014; Haberl et al. 2013; Fritz et al. 2013). Food security may be threatened if land-based mitigation displaces farming to regions with lower productivity potential, higher climatic risk and higher vulnerability. The highest increases in the population at risk of hunger are expected to occur in Sub-Saharan Africa and Asia. The land area that could be used for bioenergy or other land-based mitigation options with low to moderate risks to food security, depends on patterns of socioeconomic development, reaching limits between 1 and 4 million km^2 (IPCC 2019; Hurlbert et al. 2019; Smith et al. 2019c).

12.5.3.2 Opportunities

Many land-based mitigation options can be deployed in ways that do not compete with food security, or can even enhance food security through direct increases in yields, harvest of additional products, or maintenance of the productivity of the land resource base (Johnson et al. 2017)

- Improved forest management, reduced deforestation and forest degradation are mitigation measures applied on land that is not used intensively for food production. Harvest of non-wood forest products can enhance food security.
- Sustainable land management practices undertaken to build soil carbon, such as cover crops, grazing management and agroforestry, build soil organic matter, and thereby enhance resilience of agro-ecosystems, thus contributing to long term food security and climate change adaptation while addressing land degradation, in addition to mitigating climate change.
- Application of biochar can enhance crop yields and improve plant health, particularly in infertile acidic ferrosols commonly found in the tropics (Jeffery et al. 2017), and contribute to climate change adaptation through increased soil water holding capacity (Quin et al. 2014; Omondi et al. 2016), thus supporting food security under changing climate.
- Strategically-placed biomass crops (such as perennial grasses) and agroforestry can increase agricultural production by providing shelter to stock, windbreaks (Zheng et al. 2016; Osorio et al. 2019) and habitat for beneficial organisms such as pollinators, while providing mitigation through increased carbon stock in vegetation, and supplying biomass for bioenergy, biochar and bio-based materials.
- Integration of land-based mitigation measures can deliver benefits for food security. For example, planting biomass crops on degraded unproductive land can enhance soil organic matter while producing biomass that can by pyrolysed for bioenergy and biochar, with biochar applied to the soil to further promote rehabilitation, enabling degraded land to be subsequently utilised for food production.
- Pursuit of land degradation neutrality targets can support food security through efforts to maintain the land resource base, by avoiding, reducing and reversing land degradation (Cowie et al. 2018).

Non-bio-based mitigation options that nevertheless occupy land can also be integrated with food production to provide synergistic outcomes:

- Enhanced weathering, that is, adding ground silicate rock to soil to take up atmospheric CO_2 through chemical weathering, can supply nutrients and alleviate soil acidity, enhancing crop yields (Haque et al. 2019).; Buss et al., in review)
- Wind power production on agriculture land is well established but can face opposition due to visual landscape impacts, requiring spatial planning (Frolova et al. 2019; Hevia-Koch and Ladenburg 2019).
- Solar PV can be deployed in ways that enhance agriculture: for example, (Hassanpour Adeh et al. 2018) found that biomass production and water use efficiency of pasture were increased under elevated solar panels. Global mapping of solar panel efficiency showed that croplands having the greatest median solar potential (Adeh et al. 2019). Dual-use agrivoltaic systems are investigated which overcome previously recognised negative impact on crop growth, mainly due to shadows (Armstrong et al. 2016; Marrou et al. 2013b,a), thus alleviating land competition or other spatial constraints for solar power development (Miskin et al. 2019; Adeh et al. 2019). Assessment of the potential for optimising deployment solar PV and energy crops on abandoned cropland areas, estimates the technical potential for optimal combination at 125 EJ per year (Leirpoll et al. 2021).

Table 12.11 summarises the assessed risks, impacts and opportunities associated with different mitigation options.

Table 12.11 Impacts, risks and co-benefits associated with land occupation by mitigation options

Mitigation option	Impacts and risks	Opportunities
Non-biobased options that may displace food production		
Solar farms	Land use competition; Loss of soil carbon; heat island effect (scale dependent)	Target areas unsuitable for agriculture
Hydro power (dams)	Land use competition, displacement of natural ecosystems, CO_2 and CH_4 emissions	Water storage (including for irrigation) and regulation of water flows; Pumped storage can store excess energy from other renewable generation sources.
Non-biobased options that can (to a varying degree) be integrated with food production		
Wind turbines	May affect local/regional weather and climate (scale dependent) Impact on wildlife and visual impacts	Design and siting informed by info about visual landscape impacts, relevant habitats, and flight trajectories of migratory birds.
Solar panels	Land use competition	Integration with buildings and other infrastructure. Approaches to integration with benefits for food production is being explored
Enhanced weathering	Disturbance at sites of extraction; Ineffective in low rainfall regions	Increase crop yields and biomass production through nutrient supply and increasing pH of acid soils; synergies with biochar
Biobased options that may displace existing food production		

A/R	Land use competition, potentially leading to indirect land use change; reduced water availability; loss of biodiversity	Strategic siting to minimise adverse impacts on hydrology, land use, biodiversity
Biomass plantations	Land use competition, potentially leading to indirect land use change; reduced water availability; reduced soil fertility; loss of biodiversity	Strategic siting to minimise adverse impacts / enhance beneficial effects on land use, landscape variability, biodiversity, soil organic matter, hydrology and water quality
Biobased options that can (to a varying degree) be combined with food production		
Agroforestry	Competition with adjacent crops and pastures reduces yields	Shelter for stock and crops, diversification, biomass production, increases soil organic matter and soil fertility
Improved cropland management (increasing soil carbon stock)	Increase in nitrous oxide emissions if fertiliser used to enhance crop production	Increasing soil organic matter increases yields and resilience to drought
Modify crop rotations to include legumes and pasture phases	Reduced cereal production could lead to indirect land use change	Improves soil health and increases in soil organic matter enhance productivity and can reduce need for land use change. Reduced fertiliser requirement, less nutrient leaching Increased biodiversity and perennial vegetation enhance beneficial organisms and reduces need for pesticides
Improved grazing land management (increasing C stock in vegetation and soil)	Increase in nitrous oxide emissions if fertiliser used to enhance pasture production	Increasing soil organic matter increases pasture production
Biochar addition to soil	Land use competition if biochar is produced from purpose-grown biomass. Loss of forest carbon stock and impacts on biodiversity if biomass is harvested unsustainably.	Facilitate beneficial use of organic residues, to return nutrients to farmland. Increase land productivity to increase C sequestration in vegetation and soil. Increase nutrient-use efficiency, and reduce requirement for chemical fertiliser.
Harvest residue extraction and use for bioenergy and other bio-products	Decline in soil organic matter and soil fertility	Retain portion of stubble; return nutrients e.g. as ash
Manure management (i.e., for biogas)	Risk of methane slip	Apply digestate as soil amendment
Options that don't occupy land used for food production		
Management of organic waste (food waste, bio-solids, manure, organic component of MSW)	Can contain contaminants (heavy metals, organics, pathogens)	Processing using anaerobic digestion or pyrolysis to produce renewable gas and soil amendment, enabling return of nutrients to farmland.

Forest management and restoration	Increased fertiliser use can increase N2O emissions from soil and GHG emissions from fertiliser production. Focus on fast-growing species could reduce biodiversity and resilience.	Sustainable forest management can produce wood products that displace GHG-intensive building materials; biomass for bioenergy; enhance soil carbon, improving soil fertility, biodiversity
Reduced deforestation and degradation	Prevents expansion of land used for food (cropland and grazing land)	Protect and enhance biodiversity; Increase production of wood products
A/R on degraded non-forested land (e.g., abandoned agricultural land)	High labour and material inputs can be needed to restore productivity on degraded land. Abandoned land can support informal grazing and have significant biodiversity value. Reduced water availability	Application of biochar can re-establish nutrient cycling; bioenergy crops can add organic matter, restoring soil fertility, and can remove heavy metals, enabling food production.
Restoration & reduced conversion of coastal wetlands	Land use competition for urbanisation, infrastructure	Restoration of mangroves and marshes enhances biodiversity and protects coastal settlements contributing to climate change adaptation

Cross-Working Group Box 3: Mitigation and adaptation via the bioeconomy

Note

This box contains material produced by authors in WGII and WGIII. The content is planned to be included in a cross-WG Box placed in both WG reports.

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Executive statement

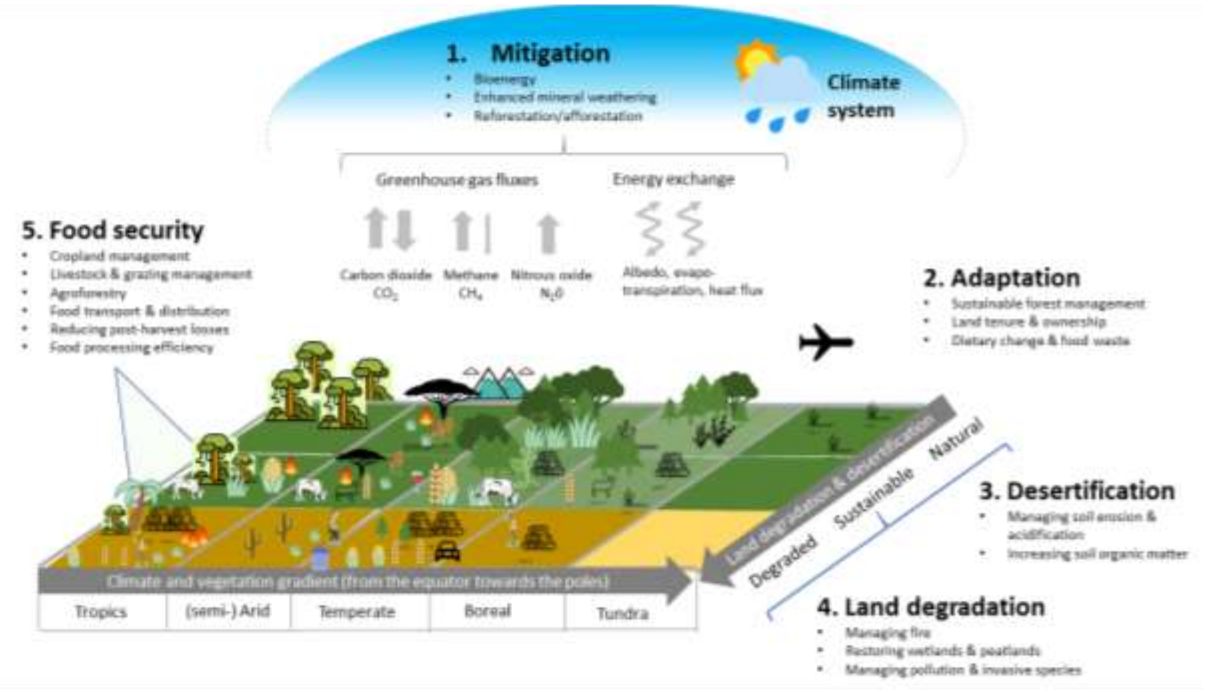
The growing bioeconomy offers both opportunities and challenges to mitigate and adapt to climate change and natural resource constraints, with increased stakeholder integration and transparent governance structures and procedures at local to global scales key to their successful resolution.

Limited global land and biomass resources accompanied by growing demands for food, feed, fibres and fuels together with prospects for a paradigm shift toward a bioeconomy and phasing out of fossil fuels set the frame for potentially fierce competition to meet diverging demands all the while climate change increasingly limits natural resource potentials.

Climate-smart agriculture and forestry, technology innovation in bio-based production within a circular economy, and international cooperation and governance of global trade in products to reflect and disincentivise their environmental and social externalities, can provide mitigation and adaptation via bioeconomy development that responds to the needs and perspectives of multiple stakeholders to achieve outcomes that maximise synergies while limiting trade-offs.

Background

There is strong evidence and agreement that climate change, population growth and changes in per capita consumption will add further pressures on managed as well as natural and semi-natural ecosystems (IPCC 2018, 2019). Several planetary boundaries will be passed if consumption and production patterns continue in their current form (eg. Mace et al. 2014; Kahiluoto et al. 2014; Steffen et al. 2015; Conijn et al. 2018; Lade et al. 2020). At the same time, many global mitigation scenarios presented in IPCC assessment reports rely heavily on the deployment of reforestation/afforestation and bioenergy, the latter often envisaged in conjunction with carbon capture and storage (BECCS), to provide CO_2 removal (CDR) from the atmosphere (Rogelj et al. 2018; Hanssen et al. 2020). Thus, the global society faces the double challenge of addressing negative land use impacts, while increasing biomass production to meet multiple demands and transforming the land sector from a source to a sink of carbon.



Cross-Working Group Box 3, Figure 1: **Illustration of the five "land challenges" that are covered by the SRCCL and the types of response options relevant to each. Note that many measures can contribute to several objectives, e.g., dietary changes can contribute to both mitigation and adaptation. Figure created by Almut Arneth, Mark Rounsevell and Eamon Haughey.**

The global society currently depends heavily on fossil fuels, with coal, oil and natural gas, which provide 85% of global primary energy use in 2017-18 (BP 2019) and feedstock for the production of, e.g., plastics and nitrogen fertilisers. The most important climate change mitigation measure is the transformation of energy, industry, and transport systems so that fossil carbon remains underground (Tong et al. 2019; Peters et al. 2020). It is not possible to maintain current systems and trends in consumption patterns, while just replacing fossil carbon with biogenic carbon. Reaching the goals of the Paris Agreement will entail transformation of all the major sectors of society (IPCC 2018; UNEP 2019). Energy efficiency and conservation measures are essential, together with technologies and systems that do not rely on carbon-based energy and materials, not the least renewable electricity supporting, inter alia, electrification of transport as well as industry processes and residential heating (IPCC 2018; UNEP 2019).

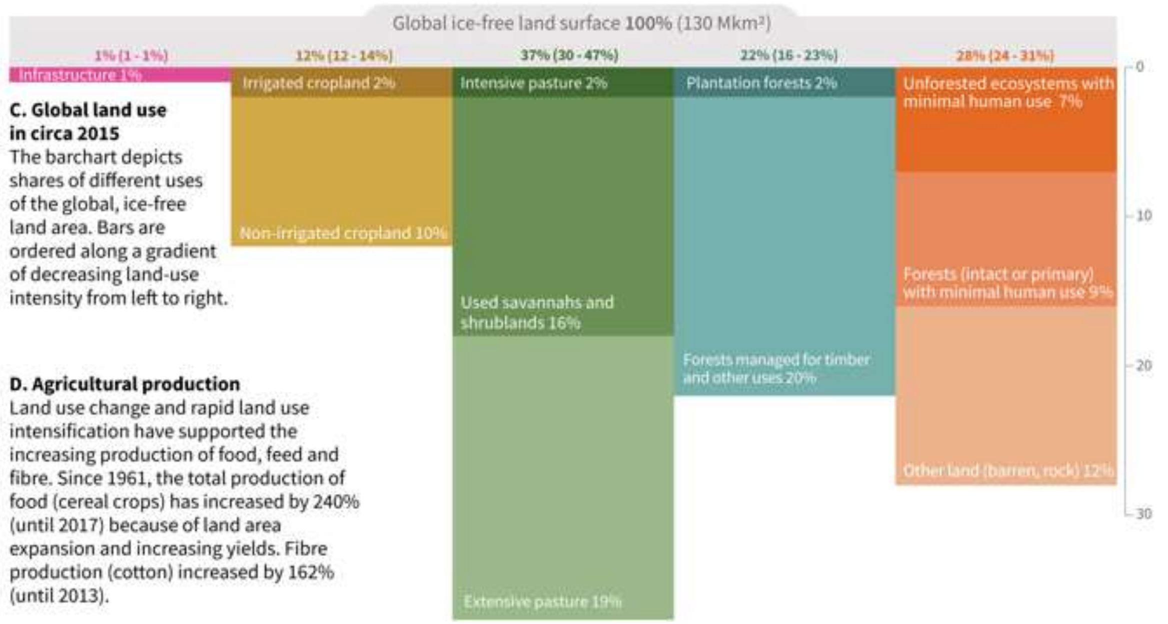
Besides food, biomass will likely be used in a multitude of applications in the coming decades while in the longer term become prioritised in applications where full decoupling from carbon is difficult to achieve (e.g., aviation, biobased plastics and chemicals) or where carbon storage is an associated benefit (e.g., wood buildings, BECCS, biochar for soil amendments). The principal circular economy objective to close the life-cycle loop of products and materials by keeping their value in the economy as long as possible - minimising waste generation and maximising recycling and reuse - can help keeping down biomass demand in many applications (Palahí et al. 2020).

Current and future global land use and vegetation cover

Globally, about 12% of the 130 Mkm^2 of ice-free surface are used for crop production, including 2% for irrigated crops; another 37% are grasslands and shrublands that are used more or less intensively; and 22% are forests managed in a variety of manners and intensities, fulfilling a multitude of functions (IPCC 2019). The remaining 28% consists of ecosystems with minimal human use, with almost half being rocks and barren land (IPCC, 2019). However, these ecosystems are also affected by climate change and other consequences of the human influence on global biogeochemical cycles. The global emissions of CO_2, CH_4 and N_2O associated with Agriculture, Forestry and Other Land Use (AFOLU) activities during 2007–2016 represent 23% of total net anthropogenic emissions (*medium confidence*). Land is simultaneously a source and a sink of CO_2; the global net land-atmosphere flux corresponds to removal of 6.0 ± 3.7 $GtCO_2yr^{-1}$ during 2007–2016 (*likely range*) (IPCC 2019).

Global land use and vegetation cover, human livelihoods and well-being, ecosystem conditions, and land-atmosphere GHG fluxes, set the frame for mitigation and adaptation via the bioeconomy. Climate change creates additional stresses on land, exacerbating existing risks to livelihoods, biodiversity, human and ecosystem health, infrastructure, and food system (IPCC 2019). The level of risks depends on the warming level and on how population, consumption, production, technological development, and land management patterns evolve. For example, the WRI estimates that about 600 Mha of additional agriculture land (one-third being cropland) can be needed by 2050 to meet the growing demand for food under a business-as-usual scenario, but also point at multiple options for meeting food demand while avoiding reforestation and restoring productivity and diversity of land and ecosystems (WRI 2018).

Although the degrees of management intensity can often be fit to the local needs of other functions and ecosystem services, at a global scale the challenge remains to avoid further deforestation and degradation of intact ecosystems, in particular biodiversity-rich systems (see WGII Chapter 2 Box ‘Nature-based solutions for climate change mitigation and adaptation’), while meeting the growing demands.



Cross-Working Group Box 3, Figure 2. Global land use and cover in ca 2015. Source: IPCC (2019)

Opportunities and challenges and trade-offs and synergies in the bioeconomy

Given the growing demand for and the finite availability of natural resources, there are invariably trade-offs that will further push toward or exceed system boundaries, unless productivities can be greatly enhanced without further undermining ecosystem services (eg. Obersteiner et al. 2016; Campbell et al. 2017; Conijn et al. 2018; Caron et al. 2018; WRI 2018; Heck et al. 2018; Smith et al. 2019). Trade-offs of the growing demand for bioproducts can lead to reduced food security and livelihoods for vulnerable groups such as Indigenous people, small-scale producers and pastoralists who can be displaced when the growing demand for biomass feedstock and carbon sequestration leads to increasing pressure on land resources. Where the growing biomass demand for producing bioproducts competes with food production this could also affect food prices (eg. To and Grafton 2015; Chakravorty et al. 2017), with possible knock-on effects related to civil unrest (Abbott et al. 2017; D'Annolfo et al. 2017). Thus, there is a need for social and environmental safeguards that takes into account land tenure arrangements, local customs and cultures, and biodiversity, among others (Tilman et al. 2011; FAO et al. 2020);

While there are trade-offs, there can also be important synergies between mitigation and adaptation and food security. For example, climate-smart agriculture (CSA) and climate-smart forestry (CSF) are approaches which attempt to increase productivity while enhancing resilience and reducing GHG emissions inherent to production (Lipper et al. 2014; Nabuurs et al. 2018; Verkerk et al. 2020). The increasing literature analysing the nexus between water, energy and food in the context of climate change consistently concludes that addressing these different domains together rather than in isolation (the default) would minimise trade-offs and enhance synergies and co-benefits (Obersteiner et al. 2016; Soto Golcher and Visseren-Hamakers 2018; D'Annolfo et al. 2017; Momblanch et al. 2019; Froese and Schilling 2019).

Explainer: Climate-smart forestry

Climate-smart forestry (CSF) considers the whole value chain from forest to wood products and energy, and puts forward a wide range of measures enabling integration of climate objectives into the forest and forest sector framework; (i) reduce greenhouse gas emissions and/or remove CO_2 from the atmosphere; (ii) adapt and build forest resilience to climate change; and (iii) sustainably increase forest productivity and incomes. The CSF *objectives can be achieved by tailoring policy measures and actions to regional circumstances in forest sectors, enabling co-benefits in nature conservation, soil protection, employment and income generation, and provision of renewable biomass for buildings and other biobased products, among others. The diversity of measures (from strict reserves to more intensively managed forests) is key for the CSF to become successful in providing mitigation and adaptation (Nabuurs et al. 2018; Verkerk et al. 2020)*

Many agroecological approaches meet the criteria for CSA and additionally address equity considerations (HLPE and Committee on World Food Security (CFS) 2019). Agroecological land use practices, such as agroforestry, intercropping, organic amendments, crop diversity, cover crops and rotational grazing, can provide mitigation and support adaption to climate change via food security, livelihoods, biodiversity and health co-benefits (Bezner Kerr et al. 2019; Bharucha et al. 2020; Clark et al. 2019; D'Annolfo et al. 2017; Garibaldi et al. 2016; HLPE 2019; Sinclair et al. 2019; Ponisio et al. 2015; Renard and Tilman 2019; WGII Chapter 2 Box 'Nature-based solutions for climate change mitigation and adaptation'). Aligning with agroecology principles, a growing body of literature investigates opportunities for strategic integration of biomass production systems (commonly perennial plants) into agricultural landscapes to provide biomass for bioenergy and other biobased products while providing co-benefits such as enhanced landscape diversity, habitat quality, retention of nutrients and sediment, erosion control, climate regulation, pollination, pest and disease control, and flood regulation (Asbjornsen et al. 2014; Englund et al. 2020; Cacho et al. 2018; Christen and Dalgaard 2013; Dauber and Miyake 2016; Holland et al. 2015; Milner et al. 2016; Ssegane et al. 2015; Zalesny et al. 2019; Ssegane and Negri 2016; Styles et al. 2016; Zumpf et al. 2017). Such approaches can help limit environmental impacts from intensive agriculture, while maintaining or increasing land productivity and biomass output.

Cross-Working Group Box 3, Figure 3. Left: High-input intensive agriculture, aiming for high yields of a few crop species, with large fields and no semi-natural habitats. Right: Agroecological agriculture, supplying a range of ecosystem services, relying on biodiversity and crop and animal diversity instead of external inputs, and integrating plant and animal production, with smaller fields and presence of semi-natural habitats. Credit: Jacques Baudry (left); Valérie Viaud (right), published in van der Werf et al. (2020).

Lack of support, policies, and incentives (both public and market-based) pose a barrier for the adoption of agroecological approaches to overcome short term losses during the transition from conventional practices before longer term benefits can accrue. Other barriers to agroecological transitions include knowledge and labour intensive methods, lack of extension support and insecure land tenure (Hernández-Morcillo et al. 2018; HLPE 2019; Jacobi et al. 2017; Kongsager 2017; Iiyama et al. 2017). Regional-level agroecology transitions may be facilitated by co-learning platforms, farmer networks, private sector and civil society groups and other incentive structures (e.g. price premiums, access to credit, regulation) (Coe et al. 2014; Mier y Terán Giménez Cacho et al. 2018; SAEPEA 2020; Valencia et al. 2019; Pérez-Marin et al. 2017; HLPE and Committee on World Food Security (CFS) 2019).

Standard impact assessment methodology such as life cycle assessment tends to favour high-input intensive agricultural systems and often insufficiently recognises the beneficial influence of agroecological approaches on ecosystem diversity and capacity to support other ecosystem services besides biomass supply (van der Werf et al. 2020). Further, as agroecological approaches can have lower yields per ha (Barbieri et al. 2019; Muller et al. 2017; Smith et al. 2020, 2019a; Seufert and Ramankutty 2017), there is concern that shifts to lower-yielding agroecological systems imply land use expansion potentially causing GHG emissions and biodiversity impacts due to conversion of natural ecosystems to agriculture land. But impact assessments of agroecology transitions are complicated since the scope of agroecology implies simultaneous broad changes in how products from land are produced and used. Changes on the demand side as well as improvements in resource-use efficiencies are also important opportunities to reduce pressures on the remaining land resources. In particular, dietary changes toward more plant-based food (where appropriate), and a reduction of food waste would have potentially high effects on the emission of GHGs in the food system with many synergies with regard to food security, adaptation, and competition for land (Smith et al. 2019c). Improved human health outcomes have also been attributed to lower levels of meat consumption, which is consistent with changing societal values refocusing from maximising food production to sustainably producing nutritious foods (Willett et al. 2019).

Agroecological approaches can support higher and more stable yields among farmers that lack economic means for investing in conventional yield-enhancing practices. Crop diversification and organic amendments can reduce input costs and help farmers overcome farmers' vulnerability to climate shocks and enhance provisioning and sustaining ecosystem services, such as pollination and yield stability (D'Annolfo et al. 2017; Sinclair et al. 2019). With the right incentives improvements can be made with regard to their profitability, provision of ecosystem services, biodiversity, etc., making them competitive with farming and forestry practices that focus on maximising output with high demands for fertilisers, agrichemicals, etc.

Explainer: Agroecology and health (Alternative: Agroecology, diet transitions and health)

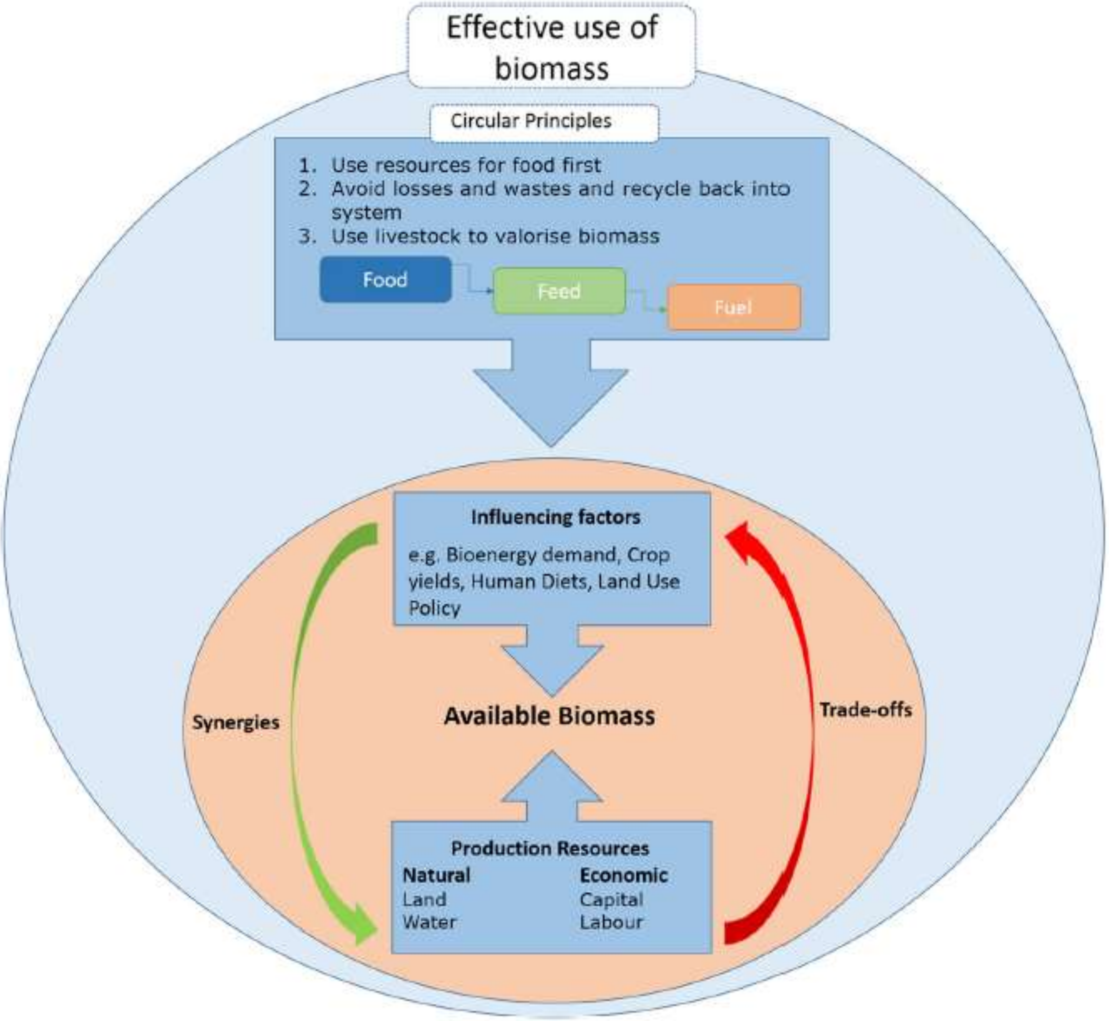
Agroecology offers co-benefits in health (medium confidence). Climate change may drive the introduction and spread of pests and diseases affecting plant and animal health, and this may trigger an increased use of pesticides (Delcour et al. 2015), veterinary drugs and antimicrobials (FAO, 2020b). In this context, agroecological approaches offer locally adapted, low-cost, biological pest control options (HLPE, 2019) with potential benefits for human and environmental health, related to the reduced use of pesticides and consequent lower risk of occupational exposure and food and water contamination (Ockleford et al. 2017, González-Alzaga et al. 2014; Mie et al. 2017). Good husbandry practices to prevent animal diseases and reduced use of antibiotics, as practiced in agroecology, lower this risk of antibiotic resistance, with potentially considerable benefits for public health (Tang et al. 2017; WHO 2017).

Many existing biobased products have significant mitigation potential. Increased use of wood in buildings can reduce GHG emissions from cement and steel production while providing long-term storage of carbon (Churkina et al. 2020). The use of biobased plastics, chemicals, and packaging could be increased and there is also scope for substituting existing biobased products with other more benign products. For example, cellulose-based textiles can replace both petroleum-based textiles and cotton, which require high amounts of water and the use of agrochemicals to ensure good yields. Advancements in the provision of novel food and feed sources (e.g. lab meat and plant based protein feed produced in green biorefineries) would also limit the pressures on finite natural resources provided the environmental footprint along their life cycles is an improvement in relation to the business-as-usual scenario (Parodi et al. 2018; Zabaniotou 2018). Enhancing and improving environmental and social standards in food-feed-fibre-fuel supply chains would lead to greater transparency of traded commodities, potentially offering ways to further reduce environmental externalities and strengthen equity. These measures could counteract some of the global pressures driven by global trade, population growth and potentially higher meat consumption in low-income countries with high levels of food insecurity. Alternatively, these lands might be utilised for biomass production to meet growing demands for biofuels and biomaterials or to restore, maintain and protect natural ecosystems providing essential ecosystem services (WGII Chapter 2 Box 'Nature-based solutions for climate change mitigation and adaptation').

Governing the solution space

Recent reviews of the literature analysing the synergies and trade-offs between concomitant demands for land suggest that solutions are highly contextualised in terms of their environmental, socioeconomic and governance-related characteristics, making it difficult to devise generic solutions. Aspects of spatial and temporal scale can further enhance the complexity, for instance where transboundary effects across jurisdictions or upstream-downstream characteristics need to be considered, or where climate change trajectories might alter relevant biogeophysical dynamics. Nonetheless, there is broad agreement that taking the needs and perspectives of multiple stakeholders into account in a transparent process during negotiations improves the chances of achieving outcomes that maximise synergies while limiting trade-offs. Yet differences in agency and power between stakeholders or anticipated changes in access to or control of resources can undermine negotiation results even if there is a common understanding of the overarching benefits of more integrated environmental agreements and the need for greater coordination and cooperation to avoid longer-term losses to all.

Decisions on land uses between food, feed, fibre, or fuel as well as for nature conservation or restoration depend on differences in perspectives and values. Because the availability of land for diverse biomass uses is invariably limited, setting priorities for land-use allocations therefore first depends on making the perspectives underlying what is considered as 'high-value' explicit (Fischer et al. 2007; Garnett et al. 2015). Decisions can then be made transparently based on societal norms and the available resource base. Prioritisation of land-use for the common good therefore requires societal consensus-building embedded in the socioeconomic and cultural fabric of regions, societies, and communities. For instance, building on work by De Boer and Van Ittersum (2018), Muscat et al. (2020) developed a hierarchical framework for European conditions that places the production of food above that of feed and fuels (Cross-Working Group Box 3 Figure 4). In this framework livestock relies on plant resources not available for human consumption (e.g. roughage) as well as on waste substrates from other biomass streams that are thus recycled back into the food system and are ultimately turned into higher-value products. The remaining land resources are deemed available for fuel production as Muscat et al. (2020) focus entirely on the food, feed, and fuel trilemma. However, this analysis does not consider the demand for other products in the growing bioeconomy, and land resources for any of these purposes are potentially also in competition with land for the provision of ecosystem services. At the same time, many nature-based solutions addressing climate risks, in particular flood risk management through floodplain restoration, saltmarshes, mangroves, or peat renaturation, have high mitigation co-benefits besides providing vital provisioning, restoring, supporting, and cultural ecosystem services, not to mention opportunities for sustainable livelihoods, such as fisheries and tourism (WGII Chapter 2 Box 'Nature-based solutions for climate change mitigation and adaptation'; UNEP 2020 in preparation).



Cross-Working Group Box 3, Figure 4. Example of a prioritisation framework for decision-making in the bioeconomy. Source: Muscat et al. (2020). Permission from authors gratefully acknowledged.

While international trade in the global economy today provides great opportunities to connect producers and consumers, effectively buffering price volatilities and potentially offering producers in low-income countries access to global markets, the continued strong demand for unsustainably produced food, biomaterials, and bioenergy, mainly from high- and middle-income countries, requires better international cooperation between nations and global governance of trade to more accurately reflect and disincentivise their environmental and social externalities. Trade of food and biomass products leading to direct and indirect land-use change in tropical forest and savanna biomes is of major concern because of the carbon emissions embedded in their provision (Hosonuma et al. 2012; Lawson et al. 2014; Henders et al. 2015; Pendrill et al. 2019; Curtis et al. 2018; Seymour and Harris 2019). Where no land-use change is at risk, there can still be trade-offs due to poor environmental and labour standards in producing countries with weaker governance structures leading to biodiversity losses or landscape degradation.

In summary, while there is significant scope for improving land use practices and produce more biomass while reducing impacts, efforts to develop technologies and systems that do not rely on carbon-based energy and materials are needed in order to keep down the biomass demand growth that will likely arise when countries seek to phase out fossil fuels. Unless such "true decarbonisation" is achieved there is a risk that concerns about negative environmental and socio-economic effects become downplayed due to a common perception that large-scale biomass use is simply necessary for maintaining lifestyles.

12.6 Other cross-sectoral implications of mitigation

This section presents further cross-sectoral considerations related to GHG mitigation. Firstly, various cross-sectoral perspectives on mitigation actions are presented. Then, sectoral policy interactions are presented. Finally, implications in terms of international trade spill-over effects and competitiveness, and finance flows and related spill-over effects at the sectoral level are addressed.

12.6.1 Cross sectoral perspectives on mitigation action

Chapters 5 to 11 present mitigation measures applicable in individual sectors, and potential co-benefits and adverse side effects[2] of these individual measures. This section builds on the sectoral analysis of mitigation action from a cross-sectoral perspective. Firstly, Section 12.6.1.1 brings together some of the observations presented in the sectoral chapters to show how different mitigation actions in different sectors can contribute to the same co-benefits and result in the same adverse side effects, thereby demonstrating the potential synergistic effects. The links between these co-benefits and adverse side effects and the SDGs is also demonstrated. In Section 12.6.1.2, the focus turns from sector-specific mitigation measures to mitigation measures which have cross-sectoral implications – including measures that have application in more than one sector and measures where implementation in one sector impacts on implementation in another. Finally, Section 12.6.1.3 notes the cross-sectoral relevance of a selection of General Purpose Technologies, a topic that is covered further in other chapters of this report.

12.6.1.1 A cross-sectoral perspective on co-benefits and adverse side effects of mitigation measures, and links the SDGs

A body of literature has been developed which addresses the *co-benefits* of climate mitigation action, (Karlsson et al. 2020). *Adverse side effects* of mitigation are also well documented. Co-benefits and adverse side-effects in individual sectors and associated with individual mitigation measures are discussed in the individual sector chapters (Sections 5.2, 6.7.7, 7.4, 7.6, 8.2, 8.4, 9.8, 10.1.1, 11.5.3), as well as in previous IPCC general and special assessment reports. The term *co-impacts* has been proposed to capture both the co-benefits and adverse side-effects of mitigation, with an alternative framing being one of multiple objectives, where climate mitigation is placed alongside other objectives when assessing policy decisions (Ürge-Vorsatz et al. 2014; Bhardwaj et al. 2019; Mayrhofer and Gupta 2016; Cohen et al. 2017).

The identification and assessment of co-benefits has been argued to serve a number of functions (Section 1.4) including using them as a leverage for securing financial support for implementation, providing justification of actions which provide a balance of both short and long-term benefits and obtaining stakeholder buy-in *(high evidence, low agreement)* (Karlsson et al. 2020). Assessment of adverse side-effects has been suggested to be useful in avoiding unforeseen negative impacts of mitigation and providing policy and decision makers with the information required to make informed trade-offs between climate and other benefits of actions (Cohen et al. 2019; Ürge-Vorsatz et al. 2014; Bhardwaj et al. 2019) *(high evidence, low agreement)*.

Various approaches to identifying and organising co-impacts in specific contexts and across the sectors have been proposed towards providing more comparable and standardised analyses. However,

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FOOTNOTE: [2] Here, the term co-benefits is used to refer to the additional benefits to society and the environment that are realised in parallel with emissions reductions, while an understanding of adverse side effects highlights where policy and decision makers are required to make trade-offs between mitigation benefits and other impacts. The choice of language differs to some degree in other chapters.

consistent quantification of co-impacts, including cost-benefit analysis, and the utilisation of the resulting information, remains a challenge (Mayrhofer and Gupta 2016; Ürge-Vorsatz et al. 2014; Floater et al. 2016; Cohen et al. 2019; Karlsson et al. 2020). This challenge is further exacerbated when considering that co-impacts of a mitigation measure in one sector can either enhance or reduce the co-impacts associated with mitigation in another, or the achievement of co-benefits in one geographic location can lead to adverse side effects in another. For example, energy efficiency implemented in various sectors reduces the demand for electricity, thereby reducing the job creation potential of renewable energy roll out. The production of lithium for batteries for energy storage has the potential to contribute to protecting water resources and reducing wastes associated with coal fired power in many parts of the world, but is creating major water and waste challenges in Bolivia, Australia, China and North America (Agusdinata et al. 2018; Kaunda 2020).

While earlier literature has suggested that co-impacts assessments can support adoption of climate mitigation action, a more recent body of literature has suggested limitations in such framing (Walker et al. 2018; Bernauer and McGrath 2016; Ryan 2015). Presenting general information on co-impacts as a component of a mitigation analysis does not always lead to increased support for climate mitigation action. Rather, the most effective framing is determined by factors relating to local context, type of mitigation action under consideration and target stakeholder group. More work has been identified to be required to bring context into planning co-impacts assessments and communication thereof (Walker et al. 2018; Bernauer and McGrath 2016; Ryan 2015) *(low evidence, low agreement).*

An area where the strong link between the cross-sectoral co-impacts of mitigation action and global government policies is being clearly considered is in the achievement of the SDGs (Chapter 1, Chapter 17, additional cross references to where SDGs covered) (Obergassel et al. 2017; Markkanen and Anger-Kraavi 2019; Smith et al. 2019b; Doukas et al. 2018). Figure 12.11 demonstrates these relationships from a cross-sectoral perspective. It shows the links between sectors which give rise to emissions, the mitigation measures that can find application in the sector, co-benefits and adverse side effects of mitigation measures and the SDGs (based on concept used in Smith et al. (2019a), and noting that the figure is not intended to be comprehensive). Such a framing of co-impacts from a cross-sectoral perspective in the context of the SDGs could help to further support climate mitigation action, particularly within the context of the Paris Agreement (Gomez-Echeverri 2018) (*medium evidence, medium agreement*). Literature sources utilised in the compilation of this diagram are presented in Supplementary Material 12.C.

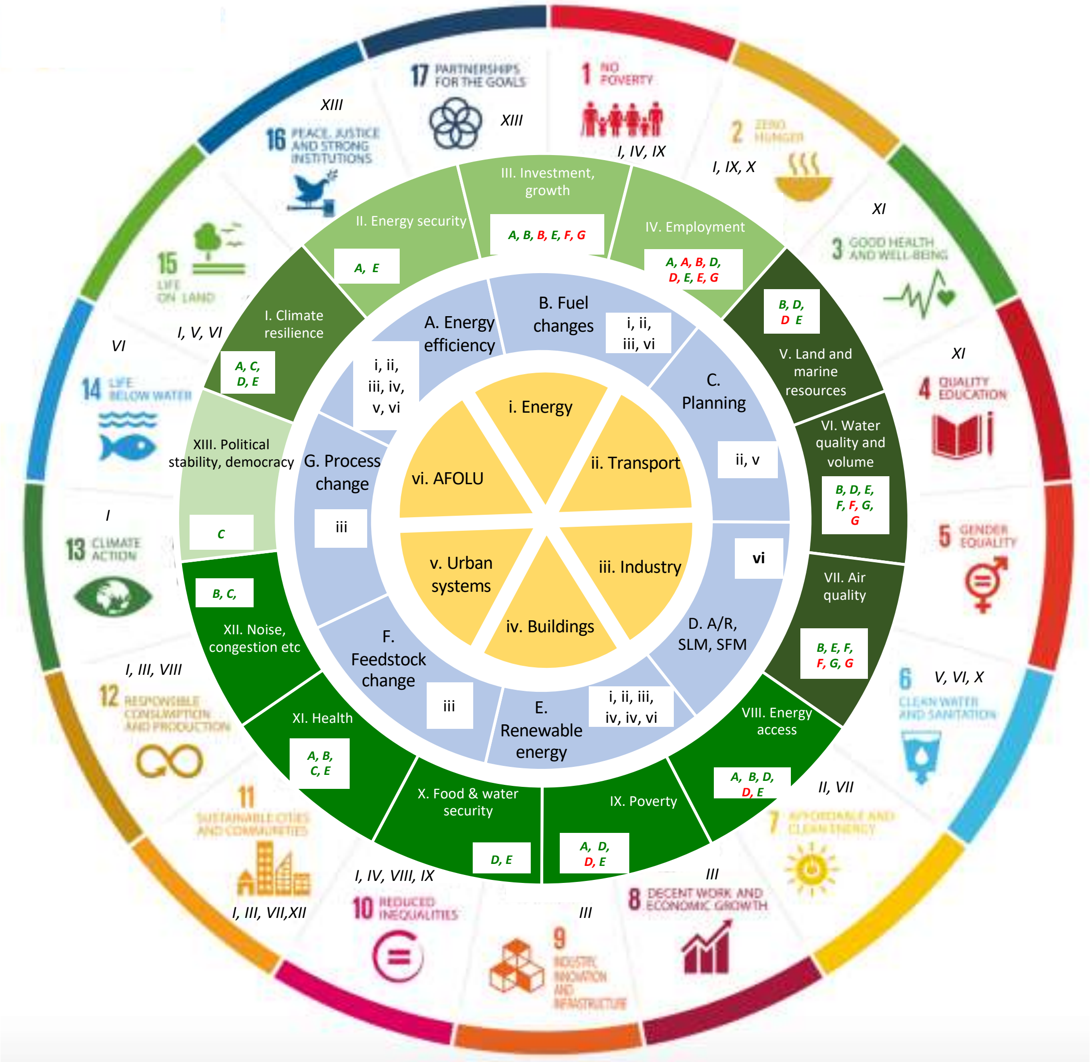


Figure 12.11 Co-benefits and adverse side effects of mitigation actions with links to the SDGs. The inner circle represents the sectors in which mitigation occurs (i to iv). The second circle shows different generic types of mitigation actions (A to G), with the small roman numerals showing which sectors they are applicable to. The third circle indicates different types of climate related co-benefits (green letters) and adverse side effects (red letters) that can be achieved through mitigation action. Here I relates to climate resilience, II-IV economic co-impacts, V-VII environmental, VIII-XII social, and XIII political and institutional, with the classification adapted from (Mayrhofer and Gupta 2016). These are again linked to the mitigation actions. The final circle maps co-benefits and adverse side-effects to the SDGs.

12.6.1.2 Mitigation measures from a cross-sectoral perspective

Three aspects of mitigation from a cross-sectoral perspective are considered, following (Barker et al. 2007):

- mitigation measures used in more than one sector;
- implications of mitigation measures for interaction and integration between sectors; and
- competition among sectors for scarce resources.

A number of mitigation measures find application in more than one sector. Renewable energy technologies such as solar and wind may be used for grid electricity supply, as embedded generation in the buildings sector and for energy supply in the agriculture sector (Chapters 6, 7, 8) (Jacobson et al. 2017; Shahsavari and Akbari 2018). Hydrogen and fuel cells, coupled with renewable energy technologies for producing the hydrogen, is being explored in transport, urban heat, industry and for balancing electricity supply (Chapters 6, 8, 11) (Dodds et al. 2015; Staffell et al. 2019). Electric vehicles are considered an option for balancing variable power (Kempton and Tomić 2005; Liu and Zhong 2019). Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) has potential application in a number of industrial processes (cement, iron and steel, petroleum refining and pulp and paper) (Chapters 6, 11) (Leeson et al. 2017; Garcia and Berghout 2019) and the fossil fuel electricity sector, although the overall potential for CCS and CCU to contribute to mitigation in the electricity sector is now considered lower than was previously thought due to the increased uptake of renewables in preference to fossil fuel (Chapter 6). When coupled with energy recovery from biomass (BECCS), CCS can provide a carbon sink (Section 12.3). On the demand side, energy efficiency options find application across the sectors, as does reducing demand for goods and services, and improving material efficiency.

A range of examples of where mitigation measures result in cross-sectoral interactions and integration is identified. The mitigation potential of electric vehicles, including plug-in hybrid hybrids, is linked to the extent of decarbonisation of the electricity grid, as well as to the liquid fuel supply emissions profile (Lutsey 2015). Making buildings energy positive, where excess energy is used to charge vehicles, can increase the potential of electric and hybrid vehicles. Advanced process control and process optimisation in industry can reduce energy demand and material inputs, which in turn can reduce emissions linked to resource extraction and manufacturing. Reductions in coal-fired power generation through replacement with renewables result in a reduction in coal mining and its associated emissions. Increased recycling results in a reduction in emissions from primary resource extraction. Certain reductions in the AFOLU sector are contingent on energy sector decarbonisation. Trees and green roofs planted to counter urban heat islands reduce the demand for energy for air conditioning and simultaneously sequester GHGs (Kim and Coseo 2018; Kuronuma et al. 2018). Recycling of organic waste avoids methane generation if the waste would have been disposed of in landfill sites, can generate renewable energy if treated through anaerobic digestion and can reduce requirements for synthetic fertiliser production if the nutrient value is recovered (Creutzig et al. 2015). Liquid transport biofuels links to the land, energy and transport sectors (see Section 12.5.2.2).

Demand-side mitigation measures, discussed in Chapter 5, also have cross-sectoral implications which need to be taken into account when calculating mitigation potentials. Residential electrification has the potential to reduce emissions associated with lighting and heating particularly in developing countries where this is currently met by fossil fuels and using inefficient technologies, but will increase demand for electricity (Chapters 5, 8, Sections 6.6.2.3, 8.4.2.1). Many industrial processes can also be electrified in the move away from fossil reductants and direct energy carriers (Chapter 11). The impact of electrification on electricity sector emissions will depend on whether generation is fossil fuels or renewables based.

At the same time, saving electricity in all sectors reduces the demand for electricity, thereby reducing mitigation potential of renewables and CCS. Demand side flexibility measures and electrification of vehicle fleets are supportive of more intermittent renewable energy supply options (Sections 6.3.7, 6.4.3.1, 10.3.4). Production of maize, wheat, rice and fresh produce requires lower energy inputs on a life cycle basis than poultry, pork and ruminant based meats (Section 12.4) (Clark and Tilman 2017). They also require less land and area per kilocalorie or protein output (Clark and Tilman 2017; Poore and Nemecek 2018), and so replacing meat with these products makes land available for sequestration, biodiversity or other societal needs. However, production of co-products of the meat industry, such as leather and wool, is reduced, resulting in a need for substitutes. Further discussion and examples of cross-sectoral implications of mitigation, with respect to cost and potentials, are presented in Section 12.2. One final example on this topic included here is that of Circular Economy (Box 12.2).

Box 12.2: Circular Economy from a Cross-Sectoral Perspective

Circular economy approaches consider the entire life cycle of goods and services, and seek to design out waste and pollution, keep products and materials in use, and regenerate natural systems (CIRAIG 2015; The Ellen MacArthur Foundation 2013). The use of Circular Economy for rethinking how society's needs for goods and services is delivered in such a way as to minimise resource use and environmental impact and maximise societal benefit has been discussed elsewhere in this assessment report (Chapter 5, Section 5.3.4.2). A wide range of potential application areas is identified, from food systems to bio-based products to plastics to metals and minerals to manufactured goods. Circular economy approaches are implicitly cross-sectoral, impacting the energy, industrial, AFOLU, waste and other sectors. They will have climate and non-climate co-benefits and trade-offs. The scientific literature mainly investigates incremental measures claiming but not demonstrating mitigation; highest mitigation potential is found in the industry, energy, and transport sector; mid-range potential in the waste and building sector; and lowest mitigation gains in agriculture (Cantzler et al. 2020). Circular economy thinking has been identified to support increased resilience to the physical effects of climate change and contribute to meeting other UN SDGs, notably SDG12 (responsible consumption and production) (The Ellen MacArthur Foundation 2019).

Circular economy approaches to deployment of low-carbon infrastructure have been brought forward as important to optimise resource use and mitigate environmental and societal impacts caused by extraction and manufacturing of composite and critical materials as well as infrastructure decommissioning (Jensen et al. 2020; Watari et al. 2019; Mignacca et al. 2020; Sica et al. 2018; Salim et al. 2019; Jensen and Skelton 2018). The circular carbon economy is an approach inspired by the circular economy principles that rely on a combination of technologies, including CCUS and other CDR options, to enable transition pathways especially relevant in economies dependent on fossil fuel exports (Lee et al. 2017; Alshammari 2020; Morrow and Thompson 2020; Zakkour et al. 2020). The integration of circular economy and bioeconomy principles (See Cross-Working Group Box 3 in this Chapter on mitigation and adaption via the bioeconomy) is conceptualised in relation to policy development (European Commission 2018) as well as COVID-19 recovery strategies (Palahí et al. 2020), emphasising the use of renewable energy sources and sustainable management of ecosystems with transformation of biological resources into food, feed, energy and biomaterials.

In terms of the third aspect, competition among sectors for scarce resources, this issue is often considered in the assessments of mitigation potentials linked to bioenergy and diets (vegetable vs. animal food products), land use and water (Section 12.5, Cross-Chapter Appendix on Biomass) (*high evidence, high agreement*). It is, however, also relevant elsewhere. Constraints have been identified in the supply of indium, tellurium, silver, lithium, nickel and platinum that are required for implementation of some specific renewable energy technologies (Moreau et al. 2019; Watari et al. 2018). Other studies have shown constraints in supply of cobalt, one of the key elements used in production of lithium-ion batteries, which has been assessed for mitigation potential in energy, transport and buildings sectors (Jaffe 2017; Olivetti et al. 2017) (*medium evidence, high agreement*), although alternatives to cobalt are being developed (Watari et al. 2018).

12.6.1.3 Cross-sectoral considerations relating to emerging general purpose technologies

General Purpose Technologies (GPTs) include, but are not limited to, additive manufacturing, artificial intelligence, biotechnology, hydrogen, digitalisation, electrification, nanotechnology and robots (de Coninck et al. 2018). Many of the individual sectoral chapters have identified the roles that such technologies can have in supporting mitigation of GHG emissions. Section 16.3 presents an overview of the individual technologies and specific applications thereof.

In this chapter, which focuses on cross-sectoral implications of mitigation, it is highlighted that certain of these GPTs will find application across the sectors, and there will be synergies and trade-offs when utilising these technologies in more than sector. One example here is the use of hydrogen as an energy carrier, which, when coupled with renewable energy, has potential for driving mitigation in energy, industry, transport, and buildings (see Box 12.3). The increased uptake of hydrogen across the economy requires establishment of hydrogen production, transport and storage infrastructure which could simultaneously support multiple sectors, although there is the potential to piggy back off existing infrastructure in some parts of the world (Alanne and Cao 2017). The benefits of digitalisation on the other hand, which has massive potential for achieving energy savings across multiple sectors, needs to be traded off against the understanding that data networks utilised to the order of 185 TWh globally in 2015, or around 1% of global electricity use. Measures are required to increase energy efficiency of these technologies (IEA 2017).

With respect to co-impacts of GPTs, the other focus of this chapter, it is highlighted that assessment of the environmental, social and economic implications of such technologies is challenging, context specific and could result in rebound effects (de Coninck et al. 2018). Each GPT would need to be explored in context of what it is being used for, and potentially in the geographical context, in order to understand the co-impacts of its use.

Box 12.3 Hydrogen in the context of cross-sectoral mitigation options

The interest in hydrogen as an intermediary energy carrier has rapidly grown in the years since 5th Assessment Report of WGIII (AR5) was published. This is reflected in this WGIII assessment report in which the term ‘hydrogen’ is used more than five times more often than in AR5. In Chapter 6 of this report, it is shown that hydrogen can be produced with low carbon impact from fossil fuels (Section 6.4.2.7), renewable electricity (Section 6.4.5.1), or biomass (Section 6.4.2.6). In the energy sector, hydrogen is one of the options for storage of energy in low-carbon electricity systems (Sections 6.4.4.1, 6.6.2.2). But, also importantly, hydrogen can be produced to be used as a fuel for sectors that are hard-to-decarbonise; that is possible directly in the form of hydrogen, but also in the form of ammonia or other energy carriers (Section 6.4.5.1). In the transport sector, fuel cell engines (Section 10.3.2) running on hydrogen can become important, especially for heavy duty vehicles (Section 10.4.3). In the industry sector hydrogen already plays an important role in the chemical sector (for ammonia and methanol production (Chapter 11 Box 11.1)) and in the fuel sector (in oil refinery processes and for biofuel production (IEA 2019b). Beyond the production of ammonia and methanol for both established and novel applications, the largest potential industrial application for low-carbon hydrogen is seen in steelmaking (Section 11.4.1.1). Hydrogen and hydrogen-derivatives can play a further role as substitute energy carrier (Section 11.3.5) and for the production of intermediate chemical products such as methanol, ethanol and ethylene when combined with CCU (Section 11.3.6). For the building sector, the exploration of the usefulness of hydrogen is in an early stage (Chapter 9 Box 9.4).

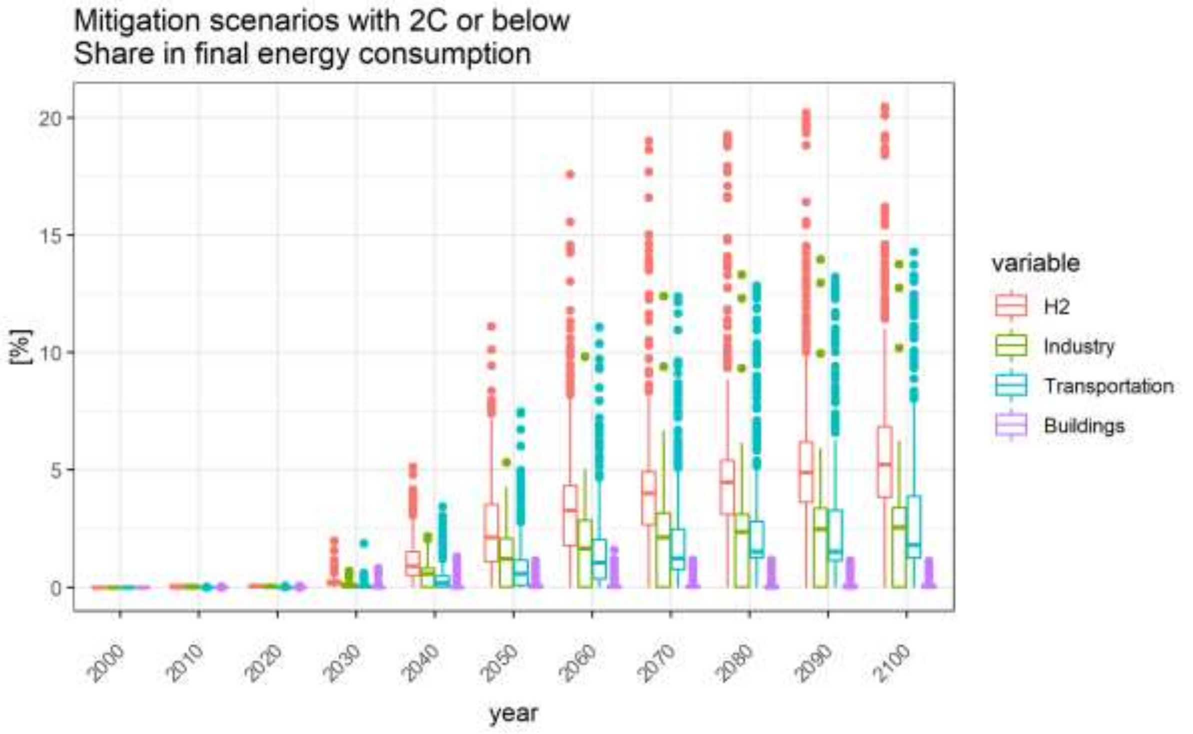
An overview report (IEA 2019b) already sees opportunities in 2030 for buildings, road freight and passenger vehicles. This report also suggests a high potential application in iron and steel production, aviation and maritime transport, and for electricity storage. Several industry roadmaps have been published that map out a possible role for hydrogen until 2050. The most well-known and ambitious is the roadmap by the Hydrogen Council (2017), which sketches a global scenario leading to 78 EJ hydrogen use in 2050, mainly for transport, industrial feedstock, industrial energy and to a lesser extent for buildings and power generation. Hydrogen makes up 18% of total final energy use in this vision. An analysis by IRENA on hydrogen from renewable sources comes to a substantially lower number: 8 EJ (excluding hydrogen use in power production and feedstock uses). On a regional level, most roadmaps and scenarios have been published for the European Union, e.g. by the Fuel Cell and

Hydrogen Joint Undertaking (FCH 2019; Blanco et al. 2018; EC 2018; Navigant 2019). All these reports have scenario variants with hydrogen share in final energy use of 10% to over 20% by 2050. When it comes to the production of low-carbon hydrogen, most attention is for the production out of electricity from renewable sources via electrolysis, so-called ‘green hydrogen’. However, ‘blue hydrogen’, produced out of natural gas with CCS is also often considered. Since a significantly increasing role for hydrogen would require considerable infrastructure investments and would affect existing trade flows in raw materials, governments have started to set up national hydrogen strategies, both potential exporting (e.g. Australia) and importing (e.g. Japan) countries (COAG Energy Council 2019; METI 2017).

As already reported in Chapter 6 (Section 6.2.4.1) production costs of green hydrogen are expected to come down from the current levels of above 100 USD MWh^{-1}. Price expectations are: 40–60 € MWh^{-1} for both green and blue hydrogen production in the EU by 2050 (Navigant 2019) with production costs already being lower in North Africa; 42–87 USD MWh^{-1} for green hydrogen in 2030 and 20 – 41 USD MWh^{-1} in 2050 (BNEF 2020); 75 € MWh^{-1} in 2030 (Glenk and Reichelstein 2019). For fossil-based technologies combined with CCS, prices may range from 33 – 80 USD MWh^{-1} (Chapter 6, Table 6.8). Such prices can make hydrogen competitive for industrial feedstock applications, and probably for several transportation modes in combination with fuel cells, but without further incentives, not necessarily for stationary applications in the coming decades: wholesale natural gas prices are expected to range from 7–31 USD MWh^{-1} across regions and scenarios, according to the World Energy Outlook (IEA 2020a); coal prices typically are a factor 2 lower than that (all fossil fuel prices refer to unabated technology and untaxed fuels). The evaluation of macro-economic impacts is relatively rare. A study by (Mayer et al. 2019) indicated that a shift to hydrogen in iron and steel production would lead to regional GDP losses in the range of 0.4–2.7% in 2050 across EU+3 with some regions making gains under a low-cost electricity scenario.

The IAM scenarios imply a modest role played by hydrogen, with some scenarios featuring higher levels of penetration. The consumption of hydrogen is projected to increase by 2050 and onwards in scenarios with a global warming of 2°C or below, and the median share of hydrogen in total final energy consumption is 2.1% in 2050 and 5.2% in 2100 (Box 12.3, Figure 1) [Numbers are based on the IPCC AR6 scenario database as of November 2019, and will change in the future]. There is large variety in hydrogen shares, but the values of 10% and more of final energy use that occur in many roadmaps are only rarely reached in the scenarios. Hydrogen is predominantly used in the industry and transportation sectors. In the scenarios, hydrogen is produced mostly by electrolysis and by biomass energy conversion with CCS (Box 12.3, Figure 1). Natural gas with CCS is expected to only play a modest role; here we observe a distinct difference between the roadmaps quoted before and the IAM results.

We conclude that there is increasing confidence that hydrogen can play a significant role, especially in the transport sector and the industrial sector. However, there is much less agreement on timing and volumes, and also there is a range of perspectives on role of the various production methods of hydrogen.



Box 12.3, Figure 1 Fraction of hydrogen (H_2, red) in total final energy consumption, and those for each sector. The upper and lower whiskers extend from the hinges no further than 1.5 times the interquartile range from the hinges; other results are presented as outliers and plotted as points.

12.6.2 Sectoral policy interactions (synergies and trade-offs)

A taxonomy of policy types and attributes is provided by Chapter 13. In addition, Chapter 13 and the sectoral chapters also provide an in-depth discussion of important mitigation policy issues such as policy overlaps, policy mixes, and policy interaction as well as policy design consideration and governance. The point of departure for the assessment in this chapter is a focus on cross-sectoral perspectives aiming at maximising policy synergies and minimising policy trade-offs.

Synergies and trade-offs resulting from mitigation policies are not clearly discernible from either the sector-level studies or the global and regional top-down studies. Instead, they would rather require a cross-sectoral integrated policy framework (von Stechow et al. 2015; Singh et al. 2019; Monier et al. 2018; Pardoe et al. 2018) or multiple-objective-multiple-impact policy assessment framework identifying key co-impacts and avoiding trade-offs (Ürge-Vorsatz et al. 2014) *(robust evidence, high agreement).*

Sectorial studies typically cover differentiated response measures while the IAM literature mostly use uniform efficient market-based measures. This has important implications for understanding the differences in magnitude and distribution of mitigation costs and potentials (Rausch and Karplus 2014; Karplus et al. 2013); Section 12.2). There is a comprehensive literature on the efficiency of uniform carbon pricing compared to sector-specific mitigation approaches but relatively less literature on the distributional impacts of carbon taxes and measures to mitigate potential adverse distributional impacts (Åhman et al. 2017; Rausch and Karplus 2014; Rausch and Reilly 2015; Mu et al. 2018; Wang et al. 2016b). For examples, in terms of cross-sectoral distributional implications studies find negative competitiveness impacts for the energy intensity industries studies (Wang et al. 2016b; Åhman et al. 2017; Rausch and Karplus 2014). *(robust evidence, medium agreement)*

Strong inter-dependencies and cross-sectoral linkages create both opportunities for synergies and the need to address trade-offs. This calls for coordinated sectoral approaches to climate change mitigation policies that mainstream these interactions (Pardoe et al. 2018). Such an approach is also called for in the context of cross-sectoral interactions of adaptation and mitigation measures, examples are agriculture, biodiversity, forests, urban, and water sectors (Di Gregorio et al. 2017; Arent et al. 2014; Berry et al. 2015). Integrated planning and cross-sectoral alignment of climate change policies are particularly evident in developing countries' NDCs pledged under the Paris Agreement, where key priority sectors such as agriculture and energy are closely aligned between the proposed mitigation and adaptation actions in the context of sustainable development and the SDGs. Example is the integration between smart agriculture and low carbon energy (Antwi-Agyei et al. 2018; England et al. 2018). Yet, there appear to be significant challenges relating to institutional capacity and resources to coordinate and implement such cross-sectoral policy alignment, particularly in developing countries context (Antwi-Agyei et al. 2018) *(robust evidence, high agreement).*

Another dimension of climate change policy interactions in the literature is related to trade-offs and synergies between climate change mitigation and other societal objectives. For example in mitigation policies related to energy, trade-offs and synergies between universal electricity access and climate change mitigation would call for complementary policies such as pro-poor tariffs, fuel subsidies, and broadly integrated policy packages (Dagnachew et al. 2018). In agriculture and forestry, research suggests that integrated policy programs enhance mitigation potentials across the land-use-agriculture-forestry nexus and lead to synergies and positive spillo-vers (Galik et al. 2019). To maximise synergies and deal with trade-offs in such a cross-sectoral context, an evidence-based/informed and holistic policy analysis approaches like nexus approaches and multi-target backcasting approaches that take into account unanticipated outcomes and indirect consequences would be needed (Klausbruckner et al. 2016; van der Voorn et al. 2020; Hoff et al. 2019; see Box 12.4) *(robust evidence, high agreement).*

Consequences of large scale land-based mitigation for food security, biodiversity, state of soil and water resources, etc. will depend on many factors, including economic development (including distributional aspects), international trade patterns, agronomic development, diets, land use governance and policy design, and not the least climate change itself (Fujimori et al. 2018; Hasegawa et al. 2018; Van Meijl et al. 2018; Winchester and Reilly 2015). Policies and regulations that address other aspects than climate change can indirectly influence the attractiveness of land based mitigation options. For example, farmers may find it attractive to shift from annual food/feed crops to perennial grasses and short rotation woody crops (suitable for bioenergy) if the previous land uses become increasingly restricted due to impacts on groundwater quality and eutrophication of water bodies (Section 12.4, Section 12.5) (*robust evidence, medium agreement).*

Finally, there are knowledge gaps in the literature particularly in relation to policy scalability and in relation to the extent and magnitude of policy interactions when scaling the policy to a level consistent with low GHG emissions pathways such as 2ºC and 1.5ºC.

Box 12.4: Case Study, Sahara Forest Project in Aqaba, Jordan

Nexus Framing

Shifting to renewable (in particular solar) energy reduces dependency on fossil fuel imports and greenhouse gas emissions, which is crucial for mitigating climate change. Employing the renewable energy for desalination of seawater and for cooling of greenhouses in integrated production systems can enhance water availability, increase crop productivity and generate co-products and co-benefits (e.g., algae, fish, dryland restoration, greening of the desert).

Nexus Opportunities

The Sahara Forest project integrated production system uses amply available natural resources, namely solar energy and seawater for improving water availability and agricultural/biomass production, that way providing new employment opportunities. Using hydroponic system and the humidity in the air, water needs for food production are 50% lower compared to other greenhouses.

Technical and Economic Nexus Solutions

Several major technologies are combined in the Sahara Forest Project, namely electricity production through the use of solar power (PV or CSP), freshwater production through seawater desalination using renewable energy, seawater-cooled greenhouses for food production, and outdoor revegetation using run-off from the greenhouses.

Stakeholders Involved

The key stakeholders which benefit from such an integrated production system are from the water sector which urgently requires an augmentation of irrigation (and other) water, as well as from the agricultural sector, which relies on the additional desalinated water to maintain and increase agricultural production. The project also involves public and private sector partners from Jordan and abroad, with little engagement of the civil society so far.

Framework Conditions

The Sahara Forest Project has been implemented at pilot scale so far, including the first pilot with one hectare and one greenhouse pilot in Qatar and a larger “launch station” with three hectares and two greenhouses in Jordan). These pilots have been funded by international organisations such as the Norwegian Ministry of Climate and Environment, Norwegian Ministry of Foreign Affairs and the European Union. Alignment with national policies, institutions and funding as well as upscaling of the project is underway or planned.

Monitoring and Evaluation and Next Steps

The multi-sectoral planning and investments that are needed to up-scale the project require cooperation among the water, agriculture, and energy sectors and an active involvement of local actors, private companies, and investors. These cooperation and involvement mechanisms are currently being established in Jordan. Given the emphasis on the economic value of the project, public-private partnerships are considered as the appropriate business and governance model, when the project is up-scaled. Scenarios for upscaling (seawater use primarily in low lying areas close to the sea, to avoid energy-intensive pumping) include 50MW of CSP, 50 hectares of greenhouses, which would produce 34,000 tons of vegetables annually, employ over 800 people, and sequester more than 8,000 tons of CO_2 annually.

Source: SFP Foundation; Hoff et al. 2019

12.6.3 International trade spill-over effects and competitiveness

International spill-overs of mitigation policies are effects that carbon-abatement measures implemented in one country have on sectors in other countries. These effects include 1) carbon leakage in manufacture, 2) the effects on energy trade flows and incomes related to fossil fuels exports from major exporters, 3) technology and knowledge spill-overs; 4) transfer of norms and preferences via various approaches to establish sustainability requirements on traded goods, e.g., EU-RED and environmental labelling systems to guide consumer choices *(robust evidence, medium agreement).* This section focuses on cross-sectoral aspects of these international spill-overs.

12.6.3.1 Cross-sectoral aspects of carbon leakage

Carbon leakage occurs when mitigation measures implemented in one country/sector lead to the rise of emissions in other countries/sectors. Three types of spill-overs are possible: 1) domestic cross-sectoral spill-overs when mitigation policy in one sector leads to the re-allocation of labour and capital towards the other sectors of the same country; 2) international spill-overs within a single sector when mitigation policy leads to substitution of domestic production of carbon-intensive goods with their imports from abroad; 3) international cross-sectoral spill-overs when mitigation policy in one sector in one country leads to the rise of emissions in other sectors in other countries. While two first types of spill-overs are described in Chapter 13, this section focuses on the third type. Though some papers address this sort of leakage, there is still significant lack of knowledge about it.

One possible channel of cross-sectoral international carbon leakage is through global value chains. Mitigation policy in one country not only leads to the shifts in competitiveness across industries producing final goods but also across those producing raw materials and intermediary goods all over the world.

This kind of leakage is especially important because the countries that provide basic materials are usually emerging or developing economies with no or limited carbon regulation. For this particular reason, foreign direct investment in developing economies usually lead to the rise in emissions (Bakhsh et al. 2017; Shahbaz et al. 2015; Kivyiro and Arminen 2014): in case of basic materials the effect of expansion of economic activity on emissions exceeds the effect of technological spill-overs, while for developed countries the effect is opposite (Shahbaz et al. 2015; Pazienza 2019). Meng et al. (2018) calculated that environmental costs for generating one unit of GDP through international trade was 1.4 higher than that through domestic production in 1995. By 2009, this difference increased to 1.8 times. Carbon leakage due to the differences in environmental regulation was the main driver of this increase.

In order to address emissions leakage through global value chains, Liu and Fan (2017) propose the value-added-based emissions accounting principle, that makes possible to account GHG emissions within the context of the economic benefit principle. Davis et al. (2011) notice that given the high level of geographical concentration of fossil fuels production and processing, regulation at the wellhead, mine mouth, or refinery might minimise transaction costs of global climate policy and the opportunities for leakage. Li et al. (2020) claim for coordinated efforts to reduce emissions in trade flows in pairs of the economies with the highest leakage such as China and the United States, China and Germany, China and Japan, Russia and Germany.

Unfortunately, these proposals either face the difficulties in collection and verification of data on emissions along value chains or require the high level of international cooperation which is hardly achievable at the moment. (Neuhoff et al. 2016; Pollitt et al. 2020) focus on the regulation of emissions embodied in global value chains through national policy instruments. They propose to implement the charge on consumption of imported basic materials into European emissions trading system. Such a charge equivalent to around €80 tCO_2^{-1} could reduce the EU's total CO_2 emissions by up to 10% by 2050 (Pollitt et al. 2020) without significant effects on competitiveness. However, such charges face the same legal and political obstacles as ordinary border carbon adjustment described in more details in Chapter 13.

Cross-sectoral effects of carbon leakage occur also through the multiplier effect, when the mitigation policy in any sector in country A leads to the increase of relative competitiveness and therefore production of the same sector A in country B that automatically leads to the expansion of economic activity in other sectors of country B. This expansion may in its turn lead to the rise of production and emissions in country A as a result of feedback effect. These spill-overs should be taken into consideration while designing climate policy as well as potential synergies that may appear due to joint efforts. However, the scale of these effect with regards to leakage shouldn't be overestimated. Even for intrasectoral leakage, many *ex ante* modelling studies generally suggest limited carbon leakage rates (see Chapter 13). Intersectoral leakage should be even less significant. Interregional spill-over and feedback effects are well-studied in China (Zhang 2017; Ning et al. 2019). Even within a single country, interregional spill-over effects are much lower than intraregional, and feedback effect are even less intense. Cross-sectoral spill-overs across national borders as a result of mitigation policy should be even smaller albeit less well-studied. In future, if the differences in carbon price between regions increase, leakage through cross-sectoral multipliers may play more important role.

Another important cross-sectoral aspect of carbon leakage concerns transport sector. If mitigation policy leads to the substitution of domestic carbon-intensive production with its exports, one of the side effects of this substitution is the rise of emissions from transportation of imported goods. International transport is responsible for about a third of worldwide trade-related emissions, and over 75 percent of emissions for major manufacturing categories (Cristea et al. 2013). Carbon leakage would potentially increase the emissions from transportation significantly as the trade of major consuming economies of the EU and US would shift towards distant trading partners in East and South Asia. Meng et al. (2018) consider more distant transportation as one of the major factors of the rise in emissions embodied in international trade from 1995 to 2009.

Emissions leakage due to international trade, investment and value chains is a significant obstacle to more ambitious climate policies in many regions. However, it doesn’t mean that disruption of trade would reduce global emissions. Zhang et al. (2020) show that deglobalisation and the drop in international trade may do it in short term, but in the longer term it will make each country to build more complete industrial systems to satisfy their final demand, although they have comparative disadvantages in some production stages, and the emissions would decrease. It should also be mentioned that international trade leads to important knowledge and technology spill-overs (subsection 12.6.3.3) and is critically important for achieving other Sustainable Development Goals (see Section 12.6.1). Any policies imposing additional barriers to international trade should be therefore implemented with great caution and require comprehensive evaluation of various economic, social and environmental effects.

12.6.3.2 The spill-over effects on the energy sector

Cross-sectoral trade-related spill-overs of mitigation policies include their effect on energy prices. Regulation of emissions of industrial producers decreases the demand for fossil fuels that would reduce prices and encourage the rise of fossil fuel consumption in regions with no or weaker climate policies *(robust evidence, medium agreement).*

Arroyo-Currás et al. (2015) study energy channel of carbon leakage with the REMIND integrated assessment model of the global economy and come to conclusion that it accounts for about 16% of the additional emission reductions of regions who introduce climate policies first. This result doesn’t differ much for different sizes and compositions of the early mover coalition.

Bauer et al. (2015) build multi-model scenario ensemble for the analysis of energy-related spill-overs of mitigation policies and reveal huge uncertainty: energy-related carbon leakage rate varies from negative values to 50% primarily depending on the trends of inter-fuel substitution.

Another kind of spill-over in energy sector concerns the “green paradox”; announcement of future climate policies causes an increase in production and trade in fossil-fuels in the short term (Jensen et al. 2015; Kotlikoff et al. 2016). The delayed carbon tax should therefore be higher than an immediately implemented carbon tax in order to achieve the same temperature target (van der Ploeg 2016). Studies also make distinction between “weak” and “strong” green paradox (Gerlagh 2011). The former refers to a short-term rise in emissions in response to climate policy, while the latter refers to rising cumulative damage.

The green paradox may work in a different way for different kinds of fossil fuels. For instance, Coulomb and Henriet (2018) show that climate policies in the transport and power-generation sectors increase the discounted profits of the owners of conventional oil and gas, compared to the no-regulation baseline but will decrease these profits for coal and unconventional oil and gas producers.

Many studies also distinguish different policy measures by the scale of green paradox they provide. The immediate carbon tax is the first-best instrument from the perspective of the global welfare. Delayed carbon tax leads to some green paradox but it is less than in the case of the support of renewables (Michielsen 2014; van der Ploeg and Rezai 2019). Among the latter, support of renewable electricity has lower green paradox than the support of biofuels (Michielsen 2014; Gronwald et al. 2017), compare subsidies to green energy and expansion of capacities of clean energy. Both policies may lead to a weak green paradox but the strong green paradox occurs only for capacity expansion. The existence of green paradox is an additional argument in favour of more decisive climate policy now: any postponements will lead to additional consumption of fossil fuels and consequently the need for more ambitious and costly efforts in future.

The effect of fossil fuel production expansion as a result of anticipated climate policy may be compensated by the effect of divestment. Delayed climate policy creates incentives for investors to divest from fossil fuels. Bauer et al. (2018) show that this divestment effect is stronger and thus announcing of climate policies leads to the reduction of energy-related emissions.

The implication of the effects of mitigation policies through the energy related spill-overs channel is of particular significance to oil-exporting countries *(medium evidence, medium agreement)*. Emissions reduction-measures lead to the decreasing demand for fossil fuels and consequently to the decrease in its exports from major oil- and gas- exporting countries. The case of Russia is one of the most illustrative. Makarov et al. (2020) show that the fulfilment of Paris Agreement parties of their NDCs would lead to 25% reduction of Russia’s energy exports by 2030 with significant reduction of its economic growth rates. At the same time, the domestic consumption of fossil fuels is anticipated to increase in response to the drop of external demand that would provoke carbon leakage (Orlov and Aaheim 2017). Such spill-overs demonstrate the need for the dialogue between exporters and importers of fossil fuels while implementing the mitigation policies.

12.6.3.3 The cross-sectoral trade-related knowledge and technology spill-overs

Technical change is one of the major channels to cope with climate change and international trade is an important driver of diffusion of knowledge and innovation. Knowledge transfer embodied in trade influence the net effect of climate policy both in technology source and receiving regions leading to various synergies and trade-offs including sectoral implications such as productivity, carbon leakage and competitiveness *(robust evidence, low agreement).*

Parrado and De Cian (2014) report that trade-driven spill-overs effects transmitted through imports of materials and equipment that result in significant inter-sectoral distributional effects meaning that some sectors witnessed great expansion in activity and emissions while others witnessed decline in activities even though the aggregated net effects for the whole economy in terms of activity and emissions are small.

An EU case study considered spill-over effects from adoption and development of clean energy technology at a much faster pace than other countries for the industries PV, wind turbines, EVs, biofuels, industry materials, batteries and advanced heating and cooking appliances. The study simulates a scenario in which EU decarbonises its energy system delivering an 80% GHG emissions reduction in 2050 from 1990 level. The results showed technology spill-overs across the considered industries leading to cumulative increase 2020–2050 from reference scenario of 1.0–1.4% in GDP, 2.1–2.3% in investment, and 0.2–0.4% in employment by clean energy technologies (EC 2017).

Brandão and Ehrl (2019) reveal that productivity of the electric power industries is much more influenced by the transfer of embodied technology from other industries than by investments of these industries themselves. They also prove that countries with the highest stock of R&D are mainly responsible for these international technology spill-overs. However, for them such spill-overs may be beneficial, too. Karkatsoulis et al. (2016) use the GEME3-RD model endogenising technology progress to compare two main strategies for the EU: being a first-mover with strong unilateral emission reduction strategy until 2030 versus postponing action for the period after 2030. Endogenous technical progress in the green technologies sector alleviates most of the negative effects of pioneering low-carbon transformation associated with loss of competitiveness and carbon leakage.

Finally, despite the growing volume of the literature on effects related to spill-overs and sectorial competitiveness, there are still large data and knowledge gaps with respect to the incidence and magnitudes of these effects.

12.6.4 Implications of finance for cross-sectoral mitigation synergies and trade-offs

Finance is a principal enabler of GHGs mitigation and an essential component of the countries NDC packages submitted under the Paris climate agreement (UNFCCC 2016). The assessment of investment requirements for mitigation along with their financing at sectoral levels are addressed in detail by sectoral chapters while the assessment of financial sources, instruments, and the overall mitigation financing gap is addressed by Chapter 15. The focus in this chapter with respect to finance is on the scope and potential for financing integrated solutions that create synergies between and among sectors.

Cross-sectoral considerations in mitigation finance are critical for the effectiveness of mitigation action as well as for balancing the often conflicting social, developmental, and environmental policy goals at the sectoral level. True measures of mitigation policy impacts and hence plans for resource mobilisation that properly address costs and benefits cannot be developed in isolation of their cross-sectoral implications. Unaddressed cross-sectoral coordination and interdependency issues are identified as major constraints in raising the necessary financial resources for mitigation in a number of countries (Bazilian et al. 2011; Welsch et al. 2014; Hoff et al. 2019)

Integrated financial solutions to leverage synergies between sectors, as opposed to purely sector-based financing at international, national, and local levels are needed to scale up GHGs mitigation potentials. At international level, Finance from Multilateral Development Banks (MDBs) is a major source of GHG mitigation finance in developing countries (World Bank Group 2015; Ha et al. 2016; Bhattacharya et al. 2016, 2018) *(medium evidence, medium agreement).* In 2018, MDBs reported a total of USD 30,165 million in financial commitments to climate change mitigation, with 71% of total mitigation finance was committed through investment loans and the rest in the form of equity, guarantees, and other instruments. GHG reductions activities eligible to MDB mitigation are limited to those compatible with low-emission pathways recognising the importance of long term structural changes, such as the shift in energy production to renewable energy technologies and the modal shift to low-carbon modes of transport leveraging both greenfield and energy efficiency projects. Sector-wise, the MDBs mitigation finance for 2018 is allocated to renewable energy (29%), Transport (18%), Energy efficiency (18%), lower-carbon and efficient energy generation (7%), agriculture, forestry and land use (8%), waste and waste-water (8%), and (12%) for other sectors (MDB 2019). Unfortunately, due to institutional and incentives issues MDBs finance mostly focused on sectoral solutions and has not been able to properly leverage cross-sectoral synergies. As a result the literature suggests an urgent need for multilateral financing institutions to align their frameworks and delivery mechanisms to facilitate cross-sectoral solutions as opposed to promoting competitions for resources among sectors (Mendez and Houghton 2020).

At the national level, applied research has shown integrated modelling of land, energy and water resources not only has the potential to identify superior solutions, but also reveals important differences in terms of investment requirements and required financing arrangements compared to the traditional sectoral financing toolkits (Welsch et al. 2014). Agriculture, forestry, and other forms of land use are promising sectors for leveraging financing solutions to scale up GHG mitigation efforts. Moving to more productive and resilient forms of land use is a complex task given the crosscutting nature of land-use that necessarily results in apparent trade-offs between mitigation, adaptation, and development objectives. Finance is one area to manage these trade-offs where there may be opportunities to redirect the hundreds of billions spend annually on land use around the world towards green activities without sacrificing either productivity or economic development (Falconer et al. 2015). Nonetheless, that would require active public support in design of land use mitigation and adaptation strategies, coordination between public and private instruments across land-use sectors, and leveraging of policy and financial instruments to redirect finance toward greener land-use practices (*limited evidence, medium agreement*). For example, Welsch et al. (2014) study on Mauritius shows that the promotion of a local biofuel industry from sugar canes could be economically favourable in the absence of water constraints, leading to reduction of petroleum imports and GHG emissions while enhancing energy security. Yet, under a water-constrained scenario as a result of climate change, the need for additional energy to expand irrigation to previously rain-fed sugar plantations and to power desalination plants yields the opposite result in terms of GHG emissions and energy costs, making biofuels a sub-optimal option and negatively affect their economics and the prospects for financing.

At the local level, integrated planning and financing are needed to achieve more sustainable outcomes. For example, at a city level integration is needed across sectors such as transport, energy systems, buildings, sewage and solid waste to optimise emissions footprint. How a city is designed will affect transportation demands, which makes it either more or less difficult to implement efficient public transportation, leading in turn to more or less emissions. Under such cases, solutions in terms of public and private investment paths and financing policies based on purely internal sector considerations are bound to cause adverse impacts on other sectors and poor overall outcomes (Gouldson et al. 2016).

Availability and access to finance are major barriers to GHG emissions mitigation across various sectors and technology options *(robust evidence, high agreement).* Resource maturity mismatch and risk exposure are two main factors limiting ability of commercial banks and other private lenders to contribute to green finance (Mazzucato and Semieniuk 2018). At all levels, mobilising the necessary resources to leverage cross-sectoral mitigation synergies would require the combination of public and private financial sources (Jensen and Dowlatabadi 2018). Traditional public financing would be required to synergise mitigation across sectors where the risk-return and time profiles of investment are not sufficiently attractive for the business sector. Over the years, private development financing through public-private partnership (PPP) and other related variants has been a growing source of finance to leverage cross-sectoral synergies and manage trade-offs (Ishiwatari et al. 2019; Attridge and Engen 2019; Anbumozhi and Timilsina 2018). Promoting such blended approach to finance along with result-based financing architectures to strengthen delivery institutions are advocated as effective means to mainstream cross-sectoral mitigation finance (Ishiwatari et al. 2019; Attridge and Engen 2019) *(limited evidence, high agreement)*. The World Bank group and the International Financial Corporation (IFC) have used the blended finance results-based approach to climate financing that addresses institutional, infrastructure, and service needs across sectors targeting developing countries and marginalised communities (GPRBA 2019; IDA 2019).

12.7 Polycentric governance of carbon dioxide removal, food systems and land-based mitigation

Effectively responding to climate change while advancing sustainable development will require coordinated efforts among a diverse set of actors on global, national and sub-national levels (Fuso Nerini et al. 2019). Both IPCC AR5 and SR1.5 defined governance broadly as ‘processes of interaction and decision-making involved in a common problem’ (Fleurbaey et al. 2014; de Coninck et al. 2018), including the selection and calibration of policy instruments (Hurlbert et al. 2019). Under the Paris Agreement governments and formal policymaking arrangements still take a central role (Oberthür and Groen 2020). Yet, the emerging paradigm of 'polycentric climate governance' highlights the growing role of sub-national and non-state actors like cities, civil society organisations, and companies, and their decisive role in experimentation, norm building, self-regulation, and knowledge diffusion (Steurer 2013; Jordan et al. 2015; Dorsch and Flachsland 2017; Carlisle and Gruby 2019). In this report, Chapters 1, 13, 14 and 17 conceptually elaborate governance arrangements in the context of sustainable development.

On a general level, it is not yet possible to conclude if emerging formal and informal networks of diverse governance actors enable or hinder the development of more effective mitigation responses, compared to earlier concepts highlighting integrated global governance visions (Keohane and Victor 2016; Morrison et al. 2019). Since the growing diversity of the governance landscape requires context-specific analyses (Markard et al. 2020; Jordan et al. 2018), this section focuses on emerging arrangements in particular domains that cut through traditional sectors – like carbon dioxide removal (Section 12.3), the food system (Section 12.4), and land-based mitigation (Section 12.5) – and how these can facilitate achievement of agreed policy objectives, inter alia by using synergies and addressing trade-offs (Section 12.6).

12.7.1 Carbon Dioxide Removal (CDR)

The mitigation targets laid down in the Paris Agreement – holding the increase in the global average temperature to well below 2°C and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels (Article 2), as well as achieving a balance between anthropogenic emissions by sources and removal by sinks of GHGs in the second half of this century (Article 4) – are impossible to achieve without CDR. Likewise, reaching a national net-zero GHG emissions target needs CDR to neutralise 'hard-to-abate' emissions, e.g., from agriculture; aviation or industrial processes (see Chapter 3 and Section 12.3).

Following AR5, widespread criticism of the use CDR in global mitigation scenarios emerged, focusing on net negative emissions pathways that allow modelling scenarios which initially overshoot carbon budgets or temperature thresholds (Anderson and Peters 2016; Geden 2016; Beck and Mahony 2018); see also Chapter 3, Section 3.2). There are concerns that the prospect of large-scale CDR could obstruct emission reduction efforts (Morrow 2014; Markusson et al. 2018) and overburden future generations (Shue 2018; Bednar et al. 2019); lead to an overreliance on technologies that are still in their infancy (Larkin et al. 2018); or – in case of deploying BECCS and afforestation at scales indicated in many mitigation scenarios – severely impact food security, biodiversity or land rights (Buck 2016; Dooley and Kartha 2018; Boysen et al. 2017; Dooley et al. 2020). Furthermore, land-based methods are often confronted with concerns about additionality and permanence of removals (Thamo and Pannell 2016; Bossio et al. 2020) (see also Section 12.7.3).

While CDR methods other than afforestation/reforestation and soil carbon sequestration still only play a minor role in UNFCCC negotiations (Fridahl 2017; Rumpel et al. 2020), the growing number of countries, cities and companies adopting net-zero emissions targets has started to shift the debate on CDR from its sole focus on modelled global pathways towards actor-specific strategies, with dedicated CDR governance emerging primarily in developed countries (Schenuit et al., *submitted*). Countries that adopted legally binding net-zero emissions targets comparatively early (like the United Kingdom and Sweden) already started to develop incentive schemes to support CDR research and demonstration, and also led local governments and companies to integrate CDR methods into their mitigation strategies (Bellamy and Geden 2019; Fridahl et al. 2020; Bellamy et al. 2021).

Given that CDR is an essential element of global mitigation pathways for 1.5°C -2°C and for reaching net zero GHG emissions both globally and nationally, the core governance question is not whether CDR should be mobilised or not, but which CDR options should be deployed by whom, by when, at which volumes and in which ways (Minx et al. 2018; Bellamy and Geden 2019). Such an approach needs to take potential co-benefits, adverse side effects, interactions with adaptation and trade-offs with SDGs (see Table 12.6) into account (Dooley and Kartha 2018; Mace et al. 2018; McLaren et al. 2019; Buck et al. 2020; Dooley et al. 2020; Honegger et al. 2020). Therefore, CDR governance should focus on responsibly incentivising research, development, demonstration and targeted near-term deployment, building on experience with already widely practiced CDR methods like afforestation/reforestation (Lomax et al. 2015; Field and Mach 2017; Bellamy 2018; von Hedemann et al. 2020).

In a polycentric system of climate governance, national and subnational levels will be of particular importance for incentivising CDR, depending on respective economic and geographic conditions, and political attitudes towards individual CDR options (Lomax et al. 2015; Bellamy and Geden 2019). Specific regulations for those CDR options posing transboundary risks have so far only been developed in the context of the London Protocol, an international treaty that explicitly regulates ocean iron fertilisation and allows parties to govern other marine CDR methods like ocean alkalinity enhancement (GESAMP 2019; Burns and Corbett 2020; see also Chapter 14).

CDR governance challenges will in many respects be similar to those around conventional mitigation options. To accelerate CDR, a political commitment to formal integration into climate policy frameworks is needed, including target setting (Geden et al. 2019; McLaren et al. 2019), emissions accounting and measurement, reporting and verification (MRV), certification schemes and standard setting, financial incentives and project-based market mechanisms. This can build on already existing rules and procedures for conventional mitigation (Honegger and Reiner 2018b; Torvanger 2019; Mace et al. 2018; Zakkour et al. 2020). Given the long time periods involved in scaling up and deploying novel technologies and approaches, there are many challenges to be tackled in research, development and demonstration to advance innovation and bring down costs (Nemet et al. 2018), including through international cooperation (see Chapters 14 and 16).

While niche markets and co-benefits can provide entry points for limited deployment of novel CDR options (Cox and Edwards 2019), carbon pricing and targeted public expenditure (e.g., through public procurement of products involving CDR) will be needed to accelerate demand-pull (Fajardy et al. 2019; Parson and Buck 2020; Rodriguez et al. 2021). Furthermore, private capital and companies, impact investors, and philanthropy may play a role in technical demonstrations and bringing down costs, as well as creating demand for carbon removal products on voluntary markets, which companies may purchase to fulfil corporate social responsibility-driven targets (Friedmann 2019; Fuss et al. 2020).

Public awareness of CDR is generally very low (Cox et al. 2020) , and when public awareness increases, the intergroup, intragroup, and social network processes will shape political attitudes on CDR(Shrum et al. 2020). Research on public attitudes on CDR has been limited and mostly conducted in Europe and the US, with research in the UK and the US suggesting some public concerns that it will slow the transition to a more sustainable society (Cox et al. 2020), and CDR techniques that are perceived as natural such as afforestation preferred to those that are perceived to tamper with nature (Wolske et al. 2019).

12.7.2 Food Systems

To support the policies outlined in Section 12.4, food system governance depends on the cooperation of actors across traditional sectors in several policy areas, in particular agriculture, nutrition, health, trade, climate, and environment (Bhunnoo 2019; Diercks et al. 2019; iPES Food 2019; Rosenzweig et al. 2020b; Termeer et al. 2018). Top-down integration, mandatory mainstreaming, or boundary-spanning structures like public-private partnerships may be introduced to promote coordination (Termeer et al. 2018). "Flow-centric" rather than territory-centric governance combined with private governance mechanisms has enabled codes of conduct and certification schemes (Eakin et al. 2017) like the *Roundtable for Sustainable Palm Oil* (RSP) as well as commodity chain transparency initiatives and platforms like *Trase*. Trade agreements are an emerging arena of governance in which improving GHG performance may be an objective, and trade agreements can involve sustainability assessments.

Research on food system governance is mostly non-empirical or case study based, which means that there is a limited understanding of which governance arrangements work in specific social and ecological contexts to produce particular food system outcomes (Delaney et al. 2018). Research has identified a number of desirable attributes in food systems governance, including adaptive governance (Termeer et al. 2018), a systems perspective (Whitfield et al. 2018), resilience (Moragues-Faus et al. 2017; Ericksen 2008; Meyer 2020); transparency, participation of civil society (Duncan 2015; Candel 2014), and cross-scale governance (Moragues-Faus et al. 2017).

Food systems governance has multiple targets and objectives, not least achieving the Sustainable Development Goals. Both governance targeting other areas of the food system, and other related systems, can have impacts on GHG emissions from food systems. For example, attempts to reduce deforestation and promote reforestation can result in a reduction of less greenhouse gas emissions from land use change; policies targeting health can contribute to diet shifts away from red meat; and national food self-sufficiency policies may also have GHG impacts. Cross-sectoral governance could enhance synergies between reduced GHG emissions from food systems and other goals; however, integrative paradigms for cross-sectoral governance between food and other sectors have faced implementation challenges (Delaney et al. 2018). For example, in the late 2000s, the water-energy-food nexus emerged as a framework for cross-sectoral governance, but has not been well integrated into policy (Urbinatti et al. 2020); perhaps because of perceptions that it is an academic concept, or that it takes a technical-administrative view of governance; simply adopting the paradigm is not sufficient to develop effective nexus governance (Cairns and Krzywoszynska 2016; Weitz et al. 2017; Pahl-Wostl et al. 2018). Other policy paradigms and theoretical frameworks that aim to integrate food systems governance include system transition, agroecology, multifunctionality in agriculture (Andrée et al. 2018), climate-smart agriculture (Taylor 2018) and the circular economy (see Box 12.2). Cross-sectoral coordination on food systems and climate governance could be aided by internal recognition and ownership by agencies, dedicated budgets to cross-sectoral projects, and consistency in budgets (Pardoe et al. 2018).; see also Box 12.

Food systems governance is still fragmented at national levels, which means that there may be a proliferation of efforts that cannot scale and are ineffective (Candel 2014). National policies can be complemented – or possibly pioneered – by initiatives at the local level (de Boer and Aiking 2018; Rose 2018). The city-region has been proposed as a useful site of food system governance (Vermeulen et al. 2020); for example, the Milan Urban Food Policy Pact involves 180 global cities committed to integrative food system strategies (Candel 2019). Local food policy groups and councils that assemble stakeholders from government, civil society, and the private sector have formed trans-local networks of place-based local food policy groups, with over two hundred food policy councils worldwide (Andrée et al. 2018). However, the fluidity and lack of clear agendas and membership structures may hinder their ability to confront fundamental structural issues like unsustainable diets or inequities in food access (Santo and Moragues-Faus 2019).

Early characterisations of food systems governance featured a binary between global and local scales, but this has been replaced by a relational approach where the local is seen a process that relies on the interconnections between scales (Lever et al. 2019). Cross-scalar governance is not simply an aggregation of local groups, but involves telecoupling of distant systems; for example, transnational NGO networks have been able to link coffee retailers in the global north with producers in the global South via international NGOs concerned about deforestation and social justice (Eakin et al. 2017). Global governance institutions like the *Committee on World Food Security* can promote policy coherence globally and reinforce accountability at all levels (McKeon 2015), as can norm-setting efforts like the 'Voluntary Guidelines for the Responsible Governance of Tenure of Land, Fisheries and Forests'. Global multi-stakeholder convenings like the *UN Food Systems Summit* can develop principles for guiding further actions. The European Commission's *Farm to Fork* strategy aims to promote policy coherence at EU and national levels, and could be the exemplar of a genuinely integrated food policy (Schebesta and Candel 2020).

Box 12.5 Case Study: The Finnish *Food2030* Strategy

In 2017, a new vision of the Finnish food system was set out in the *Food2030* strategy; to have "The best food in the world and, by 2030, Finnish consumers are eating tasty, healthy and safe Finnish food that has been produced sustainably and ethically and consumers have the ability and possibility to make informed choices" (Government of Finland 2017). *Food2030* embodies a holistic food system approach and addresses multiple outcomes of the food system, including the competitiveness of the food supply chain and the development of local, organic and climate-friendly food production and responsible and sustainable consumption.

The specific policy mix covers a range of policy instruments to enable changes in agro-food supply, processing and societal norms (Kugelberg et al. 2021a). The government provides targeted funding and knowledge support to drive technological innovations on climate solutions to reduce emissions from food and in the land use sector, the agriculture and forestry. In addition, the Finnish government applies administrative means, such as legislation, advice, guidance on public procurement and support schemes to diversify and increase organic food production to 20% of arable land, which in turn improves the opportunities of small-scale food production and processing and influence institutional behaviours to purchase local and organic food. To enable a shift in individual behaviours, the Finnish government use educational and informative instruments to shape responsible food behaviour. The Ministry of Agriculture and Forestry in collaboration with the Finnish Farmer's unions ran a two-year multi-media campaign in 2018 with key messages on sustainability, traceability and safety of the locally produced food. A "Food Facts website project", funded by the Ministry of Agriculture and Forestry in collaboration with the Natural Resources Institute Finland and the Finnish Food Safety Authority, helps to raise knowledge about food, which could shape responsible individual food behaviour, e.g., choosing local and sustainable foods and reduce food waste.

A critical enabler for developing a *shared* food system strategy across sectors and political party boundaries was the presence of a one-year inclusive, deliberative and consensual stakeholder engagement process. Hence, a wide range of stakeholders could exert real influence during the vision-building process, which resulted in a strong agreement of key policy objectives, and subsequently an important leverage point to policy change (Kugelberg et al. 2021a). Moreover, cross-sectoral coordination of *Food2030* and the government's wider climate action programs are enabled by a number of institutional mechanisms and collaborative structures, e.g. the *Advisory board for the food chain*, formally established during the agenda-setting stage of *Food2030*, interministerial committees to guide and assess policy implementation, or *Our common dining table,* a multi-stakeholder partnership that assembles 18 food system actors to engage in reflexive discussions about the Finnish food system.

Critical barriers include the weak role of integrated impact assessments to inform agenda-setting (Kugelberg et al. 2021a), which blurs a transparent overview of potential trade-offs and hidden conflicts. There were also few policy evaluations from independent organisations to inform policymaking, which makes a more progressive thinking of policy approaches less likely to occur. Monitoring and food policy evaluation is very close to Ministry in charge, which may abate reflexivity (Hildén et al. 2014). In addition, there is a lack of standardised indicators covering the whole food system, which tempers a comprehensive oversight of government's progress towards a sustainable food system (Kanter et al. 2018a). Some of the problems related to MRV are atypical for the EU and not only for Finland. However, it remains challenging for any government to evaluate the effect of a holistic food system policy on changes in ecosystems, the production and consumption side, energy and public health. To improve MRV will probably require structural changes, such as efforts to build up institutional capacity through infrastructure and application of new technology, development of standardised indicators covering the whole food system, regulations on transparency and verification, and mechanisms to enable reflexive discussions between business, farmers, NGOs and the government (Meadowcroft and Steurer 2018; Kanter et al. 2020a).

12.7.3 Land-based Mitigation

The land sector (Chapter 7) contributes to mitigation via emissions reduction and enhancement of land carbon sinks, and by providing biomass for mitigation in other sectors. Deployment of renewables, such as hydropower, solar parks, and onshore wind power, also has land related implications. Key challenges for governance of land-based mitigation include social and environmental safeguards (Larson et al. 2018; Sills et al. 2017; Duchelle et al. 2017); insufficient financing (Turnhout et al. 2017); capturing co-benefits; ensuring additionality, addressing non-permanence; monitoring, reporting, and verification; and avoiding leakage or spill-over effects. There is significant experience and learning from governance addressing bioenergy and REDD+, while soil governance in the context of climate change mitigation is an underdeveloped research field (Juerges and Hansjürgens 2018; Hurlbert et al. 2019) REDD+ can be viewed as a large-scale governance experiment or an attempt at state-building (Angelsen et al. 2017; Turnhout et al. 2017); as forest governance, it faced many early challenges, such as problems enrolling governments, society, and local forest users (Milne et al. 2019); conflict over property rights (Corbera and Schroeder 2017; Asiyanbi 2016), and violence (Cavanagh et al. 2015; Howson 2018). REDD+ implementation has paid increasing attention to forest and Indigenous peoples' concerns about justice over time, with emerging positive governance norms that require states to address these concerns (Marion Suiseeya 2017), though recognition of the ecological knowledge of forest dwellers is still insufficient (Schroeder et al. 2020).

Social and environmental safeguards for forest carbon include the UNFCCC Cancun safeguard for REDD+, and safeguard information systems and impacts reporting under the Warsaw Framework to be eligible for results-based payments (Larson et al. 2018). Empirical and case-based studies indicate that in many instances these safeguards are not working as intended. Research has pointed to several reasons why safeguards may fail, such as neo-institutional thinking, or policy naivety about creating new institutions and lack of attention to underlying, pre-existing power structures (Kemerink-Seyoum et al. 2018; Wong et al. 2019); participatory exercises that are not transformative and the lack of inclusion of women (Bee and Sijapati Basnett 2017); control by international actors and tick-box approaches to equity (Dawson et al. 2018); "do no harm" expectations that identify risks without providing for action to address those risks (Goetz et al. 2017); and a lack of provisions for enforcing compliance (Turnhout et al. 2017). MRV related to social safeguards is complex (Jagger et al. 2014) and the technical emphasis in safeguard information systems for REDD+ can lead to a narrow project focus on evidence production to demonstrate compliance, masking inequities as well as forest loss (Milne et al. 2019).

On multiple scales, MRV of both co-benefits and carbon is challenging. Monitoring costs are high and there is a disconnect between available high-level remote sensing data and the finely grained local data needed to assess benefits (Turnhout et al. 2017); for techniques like soil carbon sequestration, there is a need for flexible accounting methodologies that smallholder farmers and project developers can implement (Lee 2017). On the global scale, the question of a common accounting framework looms (Dooley and Gupta 2017), with particular challenges around carbon accounting and international trade

(Steininger et al. 2016; Wiedmann and Lenzen 2018). Permanence is also a major challenge when it comes to storing carbon in ecosystems. Policy needs to have a degree of stability to ensure permanence of carbon, and without longevity, carbon projects that successfully go through participatory processes may be left uncompleted (Vatn et al. 2017).

Certification systems and standards that focus on social benefits and environment, such as the Climate, Community, and Biodiversity (CCB) standards, are prevalent in voluntary carbon markets (Sills et al. 2017; Berners-Lee et al. 2018), as well as with bioenergy and other biobased products (de Man and German 2017; Stattman et al. 2018; Majer et al. 2018). When it comes to forest carbon, voluntary markets have helped produce improved accounting methodologies (van der Gaast et al. 2018). However, with bioenergy, private sector certifications also have weaknesses in substantive scope, implementation and market conversion that threaten their effectiveness; crucially, many criteria are unable to address the cumulative effects of impacts on multiple sites (de Man and German 2017); and the concerns of markets shape standards and exert pressure to make regulation less exacting (Winickoff and Mondou 2016).

To address the multiscalar needs of both biomass and carbon in forests and soils, governance needs to go beyond “isolationist views” looking at the project level alone and consider socio-ecological projects in the whole landscape region (Franco and Borras 2019; Hunsberger et al. 2017). REDD+ has been adopted in fragmentary ways which can allow for the displacement of deforestation, which suggests the need for interventions that address transboundary impacts and supply-and demand-side dynamics (Ingalls et al. 2018). Policymakers have paid some attention to international leakage or spillage of emissions from industry, but terrestrial leakage related to land use conversion needs more attention (Ingalls et al. 2018; Gonzalez et al. 2015). For example, if forest reference levels in the EU LULUCF Regulation incentivise Member States to constrain harvests to increase forest carbon sinks, modelling indicates considerable leakage to the rest of the world (Kallio et al. 2018). Biofuels too have provoked a large discussion on indirect land use change as well as large-scale land acquisitions, with liquid biofuel policies associated with land-use and tenure impacts in other countries (Neville and Peter 2016; Harnesk and Brogaard 2016).

Renewable energy tends to be framed as a “technology” issue, and research through the frames of public acceptance, technological adoption, and transition (Sequeira and Santos 2018), rather than focusing on it as a land use. Recent work has found that spatial processes shape the emerging energy transition, creating zones of friction between global investors, national and local governments, and civil society (McEwan 2017; Jepson and Caldas 2017). For example, hydropower and ground-based solar parks have in India involved enclosure of lands designated as waste that need to be improved, constituting forms of spatial injustice (Yenneti et al. 2016). Hydropower leads to dam-induced displacement, and though this can be addressed through compensation mechanisms governance is complicated by a lack of transparency in resettlement data (Kirchherr et al. 2016, 2019). Renewable energy production is resulting in new land conflict frontiers where degraded land is framed as having a green use, such as palm oil for biodiesel and wind in Mexico (Backhouse and Lehmann 2020); land use conflict as well as impacts on wildlife from large-scale solar installations also have emerged in the southwestern United States (Mulvaney 2017). The renewable energy transition also involves the extraction of critical minerals used in renewable energy technologies, such as lithium or cobalt. Governance challenges include the lack of transparent greenhouse gas accounting for mining activities (Lee et al. 2020a), and threats to biodiversity from land disturbance, which require strategic planning to address (Sonter et al. 2020). Strategic spatial planning is needed more generally to address trade-offs between using land for renewable energy and food: for example, agriculture and solar photovoltaics can be co-located (Barron-Gafford et al. 2019). Integrative spatial planning can integrate renewable energy with not just agriculture, but mobility and housing (Hurlbert et al. 2019).

12.7.4 Common governance challenges, barriers and enablers

Governance arrangements for carbon dioxide removal, food systems and land-based mitigation share common challenges that need to be overcome to help achieve the goals of the Paris Agreement, notably in the areas of evaluation, coordination and norm-setting. These should not be looked at in isolation, but in connection to fundamental challenges in accelerating sustainable transitions that are extensively dealt with in other parts of this report (mainly Chapters 1, 13, 14 and 17), e.g., the horizontal and vertical coordination of relevant actors (Keohane and Victor 2016; Markard et al. 2020), the inconsistency between talk, decision and actions in climate policy (Geden 2016), or limited institutional capacity of organisations tasked to fulfil governance functions (Jordan et al. 2018), an issue regularly highlighted in recent IPCC Special Reports (de Coninck et al. 2018; Hurlbert et al. 2019).

Evaluation of overall, supply-chain- or project-specific mitigation outcomes relies on transparency and robust accounting across traditional sectors and political-administrative levels. Creating reliable MRV systems, development of certification schemes or product standards, and accompanying life-cycle analyses can be expensive and time-consuming, even in developed countries with comparatively high levels of institutional capacity. Administrative procedures to establish preconditions for holding relevant actors accountable often lead to political or interest-group contestation early on (Palmer 2015). Once-agreed standards can create path-dependencies not easy to overcome when administrative and economic actors start to align their practices with agreed performance indicators. Establishing administrative modes of constant policy evaluation and pre-determined review of existing regulations can enable greater accountability and learning in environmental policymaking if powerful actors are willing to use emerging opportunity windows (Schoenefeld and Jordan 2019; Jordan et al. 2018).

The governance of carbon dioxide removal, food systems and land-based mitigation not only requires coordination across scales and actor groups. Planning also needs to deal with significant overlaps between the three domains analysed here, but trying to take complex interrelations into account does not necessarily lead to actionable knowledge (Robledo-Abad et al. 2017). For land-based mitigation and CDR, implementation at the project level complying with certification standards or social safeguards may still add up to challenges if scaled up past a certain threshold. Integrated planning is needed to avoid scalar pitfalls, and local and regional contextualised governance solutions need to be sited within a planetary frame of reference (Biermann et al. 2016). Greater planning and coordination are also needed to ensure co-benefits from land-based mitigation, CDR, and efforts to make food systems more sustainable. With low payments for carbon, for example, crop productivity may be a higher motivator than payments for farmer participation in soil carbon sequestration schemes (Lee 2017). At the same time, projects embarked on for other reasons — such as land restoration to promote food security — may find themselves with unintended climate co-benefits. To capture these co-benefits, climate change mitigation must be mainstreamed into the design of programs at multiple scales and multiple domains, in-country expertise must be strengthened, international climate finance must be increased, and monitoring must be improved (Woolf et al. 2018).

In emerging domains for governance like CDR, food systems, and land-based mitigation, global institutions, private sector networks and civil society organisations are also playing key roles in terms of norm-setting. The shared languages and theoretical frameworks, or cognitive linkages (Pattberg et al. 2018) that arise with polycentric governance can not only be helpful in creating expectations and establishing benchmarks for (in)appropriate practices where enforceable 'hard law' is missing (Karlsson-Vinkhuyzen et al. 2018; Gajevic Sayegh 2020). It can also form the basis of voluntary guidelines or niche markets (see also case study in Box 12.5). However, the ability to actually use participatory processes for developing voluntary guidelines and other participatory norm-setting endeavours varies from place to place. Social and cultural norms shape the ability of women, youth, and different ethnic groups to participate in governance fora, such as those around agroecological transformation (Anderson et al. 2019). Furthermore, establishing new norms alone does not solve structural challenges such as lack of access to food, confront power imbalances , or provide mechanisms to deal with uncooperative actors (Morrison et al. 2019).

Frequently Asked Questions

FAQ 12.1 How could new technologies to remove carbon dioxide from the atmosphere contribute to climate change mitigation?

Limiting warming to 1.5°C -2°C and achieving net-zero emissions will require efforts to draw CO_2 out of the atmosphere (carbon dioxide removal, CDR).

There are a number of CDR methods, each with different removal potentials, costs and side effects. Some biological methods used for CDR like afforestation/reforestation or wetland restoration have long been practiced. Given an expected scale of deployment, these methods could result in side effects such as biodiversity loss or food price increases. It is therefore prudent to develop new technological approaches to CDR, including Direct Air Carbon Capture and Storage (DACCS), Enhanced Mineral Weathering or Ocean Alkalinity Enhancement. Biological CDR methods are generally less expensive but more vulnerable to reversal than technological approaches.

DACCS uses chemicals that bind to CO_2 directly from the air; the CO_2 is then removed from the sorbent and stored underground or mineralised. Enhanced Mineral Weathering involves the mining of rocks containing minerals that naturally absorb CO_2 from the atmosphere over geological timescales, which are crushed to increase the surface area and spread on soils (or elsewhere) where they absorb atmospheric CO_2. Ocean Alkalinity Enhancement involves the extraction, processing, and dissolution of minerals and addition to the ocean where it enhances sequestration of CO_2 as bicarbonate and carbonate ions in the ocean.

FAQ 12.2 Why is it important to assess mitigation measures from a systemic perspective, rather than only looking at their potential to reduce Greenhouse Gas (GHG) emissions?

Mitigation measures do not only reduce GHGs, but have wider impacts. They can result in decreases or increases in GHG emissions in another sector or part of the value chain to where they are applied. They can have wider environmental (e.g., air and water pollution, biodiversity), social (e.g., employment creation, health) and economic (e.g., growth, investment) co-benefits or adverse side effects. Mitigation and adaptation can also be linked. Taking these considerations into account can help to enhance the benefits of mitigation action, and avoid unintended consequences, as well as provide a stronger case for achieving political and societal support and raising the finances required for implementation.

FAQ 12.3 Why do we need a holistic systems approach for assessing GHG emissions and mitigation opportunities from food systems?

Activities associated with the food system caused about one-third of total anthropogenic GHG emissions in 2015, distributed across all sectors. Agriculture and fisheries produce crops and animal-source food, which are partly processed in the food industry, packed, distributed, retailed, cooked, and finally eaten. Each step is associated with resource use, waste generation, and GHG emissions.

A holistic systems approach helps identify critical areas as well as novel and alternative approaches to mitigation on both supply side and demand side of the food system. But complex co-impacts need to be considered and mitigation measures tailored to the specific context. International cooperation and governance of global food trade can support both mitigation and adaptation.

There is large scope for emissions reduction in both cropland and grazing production, and also in food processing, storage and distribution. Emerging options such as plant-based alternatives to animal food products and food from cellular agriculture are receiving increasing attention, but their mitigation potential is still uncertain and depends on the GHG intensity of associated energy systems due to relatively high energy needs. Diet changes can reduce GHG emissions and also improve health in groups with excess consumption of calories and animal food products, which is mainly prevalent in developed countries. Reductions in food loss and waste can help reduce GHG emissions further.

Recommendations of buying local food and avoiding packaging can contribute to reducing GHG emissions but should not be generalised as trade-offs exist with food waste, GHG footprint at farm gate, and accessibility to diverse healthy diets.

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Supplementary Material

SM Cross sectoral perspectives

Supplementary Material 12.A: Detailed explanation of the data on costs and potentials in Section 12.2

SM 12.A.1. Introduction

In this Supplementary Material background information is provided on the way the tables in Section 12.2 have been synthesised. Section SM 12.A.2 provides information on how the extended Table 12.3 on costs and potentials of mitigation options was constructed using the input of the sectoral chapters and other information. Section SM 12.A.3 provides information on the aggregation of these costs and potentials in Table 12.4. Section

SM **12.A.4** provides information on the comparison of the sectoral results with the IAM outcomes.

SM 12.A.2. Data on emission scenarios and mitigation potentials (Table 12.2)

For the energy sector, the cost data per electricity generation technology were provided by Chapter 6. Mitigation costs were given i) for the situations that new investment in fossil-fired power plants is avoided, and ii) for the situations in which this is not the case. For the time being we assumed that both situations are each relevant for 50% of the potential. This assumption will be refined later. The potentials for each technology were taken from UNEP (2017), also published as (Blok et al. 2020).

Data for CH_4 emission reduction from coal, oil and natural gas operations for 2030 related to this study were provided by Höglund-Isaksson et al. (2020). The methane emission reduction data were converted into CO_2-eq emission reduction data, using a GWP factor of 34.75 (see Chapter 2, Box 2.12: GHG emission metrics).

The data for Agriculture, Forestry and Land-use Change were obtained from Chapter 7 (Table 7.2). The original table provides potentials below a certain cost level. They were converted into cost bins in Table 12.2 by calculating the additional potential when going from one cost level to the next. The uncertainty ranges of the cost bin were scaled down proportionally from the cumulative values. The technical and feasible potential for demand side options are taken from Table 7.5.

The data for Buildings were obtained from Chapter 9. A more extended overview, with regional breakdown, can be found in Table SM9.2 and SM9.3 This table provides a breakdown into energy efficiency vs. renewable energy integrated in buildings, and a breakdown into direct (fuel-related) and indirect (electricity-related) emission reductions. The share of energy efficiency options versus renewable energy options is 74% versus 26%. It is assumed that this breakdown is valid for both direct and indirect emission reduction options.

The provisional categorisation into cost bins is based upon the following assumptions:

- For appliances and lighting it is assumed that all of the energy efficiency improvements are achievable at costs that are smaller than the benefits over the lifetime of the equipment. This is in line with most approaches to minimum energy performance standards that work on a least life-cycle cost basis. Molenbroek et al. (2015) For new buildings, an improvement potential is available at costs of conserved energy ranging from 20 – 90 USD$ MWh^{-1}, even for retrofit up to 50% energy saving (Ürge-Vorsatz et al. 2020) 2020), which is below or at the level of the costs of energy in most countries (IEA, 2020). Therefore, this potential was placed in the cost bin below zero. For existing buildings, there have been many examples of deep retrofits which additional costs per CO_2 abated are not significantly higher than those of shallow retrofits, however for the whole stock they tend to be higher than those of new buildings, in the range of 0-20 USD$ tCO_2^{-1} avoided.
- Integrated photovoltaic solar energy application costs are already near the level of electricity costs (Chapter 9 and Chapter 6). With expected further cost reductions, it is likely that for this application the benefits will also exceed the costs.
- For the production of solar and bioenergy heat, it is likely that benefits will not balance the costs, however the share of photovoltaic solar was much higher than that of solar heat, therefore the renewable energy have been placed in the categories of <0 USD$ tCO_2^{-1} avoided.

For the transport sector, a provisional assessment was made by Chapter 12, partly based on information available in Chapter 10:

- Data for the technical options for passenger cars were taken from ICCT (2019). The authors explore the potential of rapid further fuel economy technologies (50% reduction in new passenger vehicle per kilometre CO_2 emissions in 2030 compared to 2005) and fast adoption of electric vehicles (35% of sales in 2030). This share in new vehicle sales is comparable with what is assumed in Chapter 10 (30%) and as estimated in BNEF (2020). For heavy duty trucks the reduction of new per kilometre CO_2 emissions is 35% in 2035 compared to 2005, and a share of electric vehicles sales of 19% in 2030. The emission reduction in freight transport is comparable to the potential calculated in IEA (2020b). According to ICCT (2019) the fuel economy measures are cost-effective, i.e. negative costs per tonne of CO_2 avoided. For electric vehicles, it is expected that price-parity with conventional vehicles is reached in the mid-2020s (BNEF 2020), meaning that life-cycle benefits will already exceed costs before that.

- Data for the impact of modal shifts in passenger transport are taken from Mason et al. (2015). They calculate that costs, both for the shift to public transport and the shift to cycling, are lower than for the transport by passenger cars.
- For aviation, limited estimates are available. Emission reduction potential (excluding biofuels) in the range of 0.12 – 0.32 $GtCO_2$ are reported (Fleming and de Lépinay 2019; ICCT 2020; IEA 2020b), but underlying assumptions are not very well documented. More information would be desirable here.
- For shipping, in Chapter 10 an emission reduction potential of 39% (range 30 – 56%) compared to business-as-usual is quoted (Section 10.6.4), which translates to 0.7 $GtCO_2$ (range 0.5 – 1.0 $GtCO_2$), using an average business-as-usual emissions of approx.1.8 $GtCO_2$ (Bouman et al. 2017). The review study by Bouman et al. (2017) quotes earlier studies "that it is possible to improve energy efficiency and reduce emissions in a cost effective manner, either with zero costs or with net cost savings", so it is assumed that the potential mostly will be in the below-zero cost bin. It is assumed that 1/3 of the potential is for biofuels, which comes at higher costs.
- For biofuels, the IRENA (2016) estimate that 10% of the fuels for the transport sector can be provided by biofuels in 2030 is followed. For the calculation of avoided CO_2 emissions, the calculation in UNEP (2017) is used. Prices of transportation biofuels are currently higher than regular fuels, but could come closer to parity with regular fuels (IEA Bioenergy 2020).

The data for Industry were obtained from Chapter 11 authors. The baseline shows an increase in CO_2 emissions from 2017 to 2030 of 28%. For comparison, industrial final energy use increases by 24% in the Current Policies scenario of the World Energy Outlook 2019 (IEA 2019a) (no data on CO_2 emissions available for the latter). This suggests that the Chapter 11 baseline emissions are slightly higher than in the World Energy Outlook (assuming no major fuel shifts in the Current Policies scenario).

The original table from Chapter 11 was converted to the more compact set of data in Table 12.2 as follows:

- The category Production decarbonisation for the Chemical industry was assumed to be 2/3 CCS and clean hydrogen, and for 1/3 biocarbon.
- The category Material efficiency and recycling for the Non-ferrous metals industry was assumed to be ½ material efficiency and ½ recycling.
- The category Other fuel switching for Other industry was assumed to be ½ bioenergy and ½ CCS.

Data for HFC emission reduction were taken from Purohit and Höglund-Isaksson (2017).

Data for CH_4 emission reduction from solid waste and waste water were taken from Höglund-Isaksson et al. (2020) and processed using the approach described previously for the Energy sector, using a GWP conversion factor for biogenic methane of 32.

The information for direct air capture and enhanced weathering is that reported in Section 12.3.

SM 12.A.3. Analysis of overlaps and interactions between sectors

In order to determine sectoral aggregates, the overlap and interactions between options needs to be taken into account.

For the electricity sector, the average values were summed, assuming that all options can be applied in a complementary way. For the lower end, the lower values for wind and solar energy were used, while average values were used for the rest. It is clear that for the other values uncertainties also exist, but these are small compared to the uncertainties for solar and wind.

For the other energy sector emissions, from coal, oil and natural gas operations, the situation is more complex. The total emission reduction potential for fossil fuels in the other sectors is over 60%. Would that latter be realised, this would obviously lead to a reduction of the potential reported here. However, reducing fossil fuel use also leads to a reduction in the upstream CH_4 emissions, so in the case of reducing fossil fuel use, these upstream emissions will also be avoided. As these emission reductions are normally not taken into account in the potential estimates for end-use sectors, the numbers presented provide an underestimate of the emission reduction potential in this category.

For the Agriculture, Forestry and Land-use Change sectors, the potentials have been aggregated, as interactions were already taken into account in Chapter 7. The numbers for BECCS are excluded from the aggregation, as these overlap with those for the Electricity and Industry sectors. The combined potential for these two sectors is lower than what is presented in Chapter 7, probably as a result of bottlenecks in the application of the bioenergy with CCS, not in production.

For buildings, only direct emission reductions have been included in the aggregation across sectors. The indirect supply side options (mainly rooftop PV) overlap with the PV potential already identified for the Energy sector. The indirect demand side emission reductions (efficient appliances etc.) will largely overlap with carbon-free power production.

For transport, there may be some interaction between technical options and modal shift options. This effect is estimated to be less than 0.2 $GtCO_2$. Switching to electric vehicles will lead to additional emissions in the power sector, this is taken into account in the underlying analysis (the range in the potential is caused by different assumptions on the carbon intensity of the power sector).

For industry, all emission reductions are fuel-related. Part of the potential is related to electrification, the emissions reduction caused by this is about 1.1 $GtCO_2$. Depending on the technology applied, this will lead to additional electricity use in the industrial sector. This may be (more than) compensated by more efficient use of electricity, an option that is not quantified in this analysis.

SM 12.A.4. Construction of Figure SPM.9 for the Summary for Policy Makers

Figure SPM.9 is directly derived from Table 12.2, with the following adaptations:

- The mid-range numbers were used. If no mid-range was provided the average of the low and high extremes was selected.
- For the demand-side options in AFOLU the so-called feasible potential was used, and if that was not available the technical potential. To avoid confusion, these were presented with a different colour.
- Options for which no potential was estimated were excluded from the Figure, to avoid the impression that the potential is zero.
- Options with potential <<1 were excluded.
- The BECCS potential in the AFOLU sector was not included in the figure, as it overlaps large with similar potentials in the Energy and Industry sectors.
- For options stretching over more than one cost range, the middle range was selected.

Supplementary Material 12.B: Feasibility assessment of DACCS and EW as presented in Section 12.3.2.4

The following tables (SM 12.C Table 1 and SM 12.C Table 2) present the line of sight with references underlying the feasibility assessment of Direct Air Carbon Capture and Storage (DACCS) and Enhanced Weathering (EW), presented in Section 12.3.2.4 Table 12.5. See Chapter 6 for the presentation of the feasibility assessment framework.

SM 12.B Table 1 Feasibility assessment of Direct Air Carbon Capture and Storage. Yellow shading signifies the indicator has a positive impact on the feasibility of the option. Light brown shading signifies the indicator has mixed positive and negative effect on the feasibility of the option. Dark brown shading indicates the indicator has a negative impact on the feasibility of the option. NA signifies that the indicator is not applicable for the option, NE indicates no evidence, and LE means limited evidence whether the indicator affects the feasibility of the option. Level of agreement and evidence are indicated on a scale of 1-5 from low/limited to high/robust.

		Direct Air Carbon Capture and Storage				
Dimension	**Indicators**	**Feasibility barriers or enablers**	**Notes / Role of context, scale, time, temperature goal**	**Agreement**	**Evidence**	**Line of sight**
Geophysical	Physical potential	🟨	Depends on where DACCS is employed	5	3	(Fuss et al. 2018)
	Geophysical resources (including geological storage capacity)	🟨	Depends on where DACCS is employed	5	3	(Dooley 2013; Kearns et al. 2017)
	Land use	🟨		5	4	(Socolow et al. 2011; Smith et al. 2016; Fuss et al. 2018)
Environmental-ecological	Air pollution	NE				
	Toxic waste, ecotoxicity and eutrophication	NE				
	Water quantity and quality	🟧	Depends on the technology; some technologies consume water while others generate it	3	3	(Smith et al. 2016; Fasihi et al. 2019; Fuhrman et al. 2020)
	Biodiversity	NE				
Technological	Simplicity	NE				
	Technology scalability	🟨		5	4	(Fasihi et al. 2019; Nemet 2019)
	Maturity and technology readiness	🟨		5	3	(Royal Society and Royal Academy of Engineering 2018; National Academies of Sciences Engineering and Medicine 2019; Rhodium Group 2019)
Economic	Costs in 2030 and long term	🟫		2	2	(Sinha et al. 2017; Fuss et al. 2018; Keith et al. 2018; National Academies of Sciences Engineering and Medicine 2019)

	Employment effects and economic growth	🟨		5	3	(Rhodium Group 2019)
Socio-cultural	Public acceptance	🟫	Very few countries examined	2	2	(Cox et al. 2020)
	Effects on health and wellbeing	**NE**				
	Distributional effects	**NE**				
Institutional	Political acceptance	**NE**				
	Institutional capacity and governance, cross-sectoral coordination	**NE**				
	Legal and administrative feasibility	**NE**				

SM 12.B Table 2 Feasibility assessment of Enhanced Weathering. Yellow shading signifies the indicator has a positive impact on the feasibility of the option. Light brown shading signifies the indicator has mixed positive and negative effect on the feasibility of the option. Dark brown shading indicates the indicator has a negative impact on the feasibility of the option. NA signifies that the indicator is not applicable for the option, NE indicates no evidence, and LE means limited evidence whether the indicator affects the feasibility of the option. Level of agreement and evidence are indicated on a scale of 1-5 from low/limited to high/robust.

		Enhanced Weathering				
Dimension	**Indicators**	**Feasibility barriers or enablers**	**Notes / Role of context, scale, time, temperature goal**	**Agreement**	**Evidence**	**Line of sight**
Geophysical	Physical potential	NA				
	Geophysical resources (including geological storage capacity)	🟨	Silicate rock formations, silicate rock dust stockpiles, C&D waste	5	5	(Lackner et al. 1995; Renforth 2012; Taylor et al. 2016; Kelemen et al. 2019; Renforth 2019; Beerling et al. 2020)
	Land use	🟨	Existing croplands, co-deployable with afforestation/reforestation/BECCS/biochar	5	5	(Beerling et al. 2018; Hartmann et al. 2013; Strefler et al. 2018; Renforth 2019; Amann

		🟨				et al. 2020; Beerling et al. 2020)
Environmental-ecological	Air pollution	🟧	Air-blown rock dust, reduction in NOx emissions	2	3	
	Toxic waste, ecotoxicity and eutrophication	NE				
	Water quantity and quality	NE				
	Biodiversity	NA				
Technological	Simplicity	🟨	Straight forward, utilises existing technology	5	5	(Renforth 2012; Strefler et al. 2018)
	Technology scalability	🟨	Upscaling is potentially straight forward, infrastructure (e.g. road rail) already in place for handling harvests of equivalent mass	4	4	
	Maturity and technology readiness	🟨	Components of technology are mature, including the application of minerals to land. However, commercially operating supply chains for CO$_2$ removal are immature, longitudinal field scale demonstrations are required	5	5	(Royal Society and Royal Academy of Engineering 2018)
Economic	Costs in 2030 and long term	🟧	Developed countries: $160-190 tCO$_2^{-1}$ removed; developing countries cheaper: $55-120 tCO$_2^{-1}$ removed	3	3	(Beerling et al. 2020)
	Employment effects and economic growth	NE	Potential to increase employment in mining, transport sectors			
Socio-cultural	Public acceptance	LE	US and UK Public support for limited trials with careful monitoring, public concern if it involved opening new mines	3	4	(Pidgeon and Spence 2017; Cox et al. 2020)
	Effects on health and wellbeing	NE	Respirable dust means caution required during application, not a barrier to implementation			
	Distributional effects	LE	Investment incentives for enhanced weathering are potentially broader and include increased yields, improved soils, reduced agrochemical costs, improved runoff water quality in environmentally sensitive areas and potential benefits to marine life	3		(Beerling et al. 2018)
Institutional	Political acceptance	LE	Non-climate co-benefits may be valuable in terms of the policy ‘demand pull’	3	3	(Cox and Edwards 2019)
	Institutional capacity and governance, cross-sectoral coordination	NE				
	Legal and administrative feasibility	NE	Probably not limiting for natural silicate rock given existing protocols for fertiliser, potentially limiting for alkaline wastes/by-products			

Supplementary Material 12.C: The link between co-benefits and adverse side effects of mitigation actions and the SDGs

The following tables (SM 12.C Table 1 and SM 12.C Table 2) present examples of the information used in the construction of SM 12.C Table 1provides examples of mitigation actions that fall into the groups of actions shown SM 12.C Table 2 in the different sectors. Note that the mapping is intended to be illustrative and is not intended to be exhaustive.

SM 12.C Table 1 Examples of mitigation actions in the different sectors

Types of mitigation actions	**Examples of sector application**
A. Energy efficiency	**Energy:** Reducing the auxiliary load of fossil and renewable power stations **Transport:** Advances in vehicle technologies to make them more fuel efficient such as vehicle light weighting, accessory load management, powertrain systems optimisations, and aerodynamics (Kammen and Sunter 2016) **Industry:** Efficient motors and pumps, increased heat integration. **Buildings:** Thermal insulation and efficient HVAC systems (Kammen and Sunter 2016; Cao et al. 2016) **Urban systems:** (Amado et al. 2016) **AFOLU:** Increased efficiency in pumping
B. Fuel changes	**Transport:** Shift from liquid fossil fuels to biofuels, synthetic fuels produced from renewables and CO_2 recycling **Industry:** Shift to natural gas and bioenergy as sources of energy in industrial processes (Åhman et al. 2017)
C. Planning	**Transport:** Improved public transport systems **Urban systems:** Including GHG considerations in decisions surrounding urban development intensity (Wang et al. 2015)
D. AFOLU actions	**AFOLU:** Wetland restoration, biochar and BECCCS (Smith et al. 2019b)
E. Renewable energy	**Energy:** Shift from fossil fuels to the various renewable alternatives such as wind, solar, geothermal, wave and bioenergy options **Transport:** Electric vehicles, biofuels in land and aviation transport (Mathiesen et al. 2015) **Industry:** Use of bioenergy and other renewable sources for heating and cooling (Fais et al. 2016), producing hydrocarbons in processes based on renewable electricity (e.g. methane from power-to-gas conversion)(Åhman et al. 2017). **Buildings:** Distributed/embedded renewable energy technologies coupled with smart grids (Cao et al. 2016) **Urban systems:** Urban solar thermal energy, for space and domestic water heating (Kammen and Sunter 2016) **AFOLU:** Solar PV for pumping, solar energy in greenhouses (Hassanien et al. 2016)
F. Feedstock change	**Industry:** Replacing fossil feedstock with biomass in the petrochemicals industry (Åhman et al. 2017)

G. Process change	**Industry:** Producing virgin steel without process-related emissions through the introduction of new concepts such as process-integrated CCS and electrification (electrowinning) or bio- methane/hydrogen direct reduction (DRI) (Åhman et al. 2017).

SM 12.C Table 2 Examples of co-benefits and adverse side effects, linked to different mitigation actions. The letters A-G link to the groups of mitigation actions shown in Table SM 12C Table 1.

Types of Co-benefits	**Examples**	**Examples of adverse side effects**
I. Climate resilience	Improved insulation to reduce building energy demand also provides resilience to increasing temperatures (A) Integrated planning of urban systems and infrastructure to mitigate emissions can incorporate climate resilience (C) Afforestation and reforestation in the AFOLU sector can help biodiversity, reduce erosion and increase land productivity, thereby increasing climate resilience (D) Distributed renewable energy infrastructure is less vulnerable to climate impacts than large centralised infrastructure (E)	
II. Energy security	Energy efficiency results in a lower primary energy demand to achieve the same productive energy and hence increases energy security (A). Renewable energy reduces requirements for fossil inputs which may be in finite supply, imported, and/or vulnerable to policy, legislation and penalties on fossil fuels. This can contribute to greater energy security for a country or region (B).	
III. Investment, growth	More efficient energy use, switching to more efficient and locally sourced fuels and renewable energy options can be linked to greater resource efficiency and lower productive energy costs, and thus can have positive economic growth outcomes (A, B, E).	Depending on the application, switching to alternative fuels, alternative feedstocks and new processes may require significant technology development, high capital inputs and be more expensive, resulting in negative impacts on investment and growth (B, F, G).
IV. Employment	Job opportunities can be created in energy efficiency, AFOLU and renewable energy actions (A, D, E)	Job losses can be experienced during the transition to increased efficiency, alternative fuels and processing routes (A, B, D, E, G). The growing literature on “just transitions” describes this concern in the energy sector. Reducing deforestation could lead to reduced employment opportunities to those dependent on firewood for sale (D)

V. Biodiversity, ecosystem services, soil	Many alternative fuels, various actions in the AFOLU sector and renewable energy options require lower inputs of primary resources and thus have a lower impact on biodiversity, ecosystem services and soil (B, D, E)	
VI. Water pollution	Alternative fuels, feedstocks and processes, actions in the AFOLU sector and renewable energy options may require lower water inputs and give rise to lower pollutant loads than the options they are replacing (B, E, D, F, G)	Although alternative feedstocks and processes may be less GHG intensive than current options, some could have potential for negative water pollution impacts (F, G).
VII. Air pollution	Alternative fuels, feedstocks and processes, and renewable energy options may give rise to lower air pollutant loads than the options they are replacing, which are often based on fossil fuels (B, E, F, G)	Although alternative feedstocks and processes may be less GHG intensive than current options, there is potential for greater local air pollutant impacts. An example here is diesel vehicles which have lower GHGs but higher local air pollutants than petroleum ones (F, G).
VIII. Energy access	Energy efficiency, alternative fuels and renewable options can provide affordable and reliable energy supply to areas that are both currently served and unserved with electricity and other energy carriers (ABE) Sustainable harvesting of forestry resources can contribute to energy access in communities reliant on these sources for supply (E).	Reducing deforestation could lead to reduced energy access for those dependent on collecting firewood from forests for use (D)
IX. Poverty alleviation	Energy efficient technologies can contribute to lower costs of energy, thereby increasing access and reducing poverty (A) Afforestation can provide increased access to firewood and protection of diversity which can lead to positive economic outcomes (D) (Smith et al. 2019b). Renewable energy can help increased energy access which can contribute to poverty alleviation through access to lighting, pumping for agriculture etc (E)	Reducing deforestation could lead to reduced incomes and increased hardship for those dependent on firewood for use and sale (D)
X. Food & water security	Climate mitigation interventions in the AFOLU sector can help increase land productivity, reduce erosion, and protect biodiversity, which can all contribute to enhanced food and water security (D) (Smith et al. 2019b) Renewable energy technologies typically require lower water inputs than fossil fuel options, thereby increasing water availability for other uses and hence increasing water security (E).	

XI. Health	Energy efficiency, alternative fuels and renewable energies can result in lower indoor and outdoor air pollution impacts, thereby contributing to positive health outcomes (A, B, E). Agriculture mitigation options can include lower pesticide and fertiliser application rates, thereby reducing negative impacts on health of surrounding communities (D)	
XII. Noise, congestion etc	Alternative fuel vehicles and integrated urban planning approaches can help reduce noise and congestion (B, C).	
XIII. Political stability, democracy	Integrated planning approaches which include climate mitigation considerations can support political stability and democracy in decision making (C)	

Sources include: (Buonocore et al. 2016; Ürge-Vorsatz et al. 2014; Åhman et al. 2017; Smith et al. 2019b; Kerr et al. 2017; Karlsson et al. 2020; Cohen et al. 2019; Forouli et al. 2019; Van de Ven et al. 2019)