Chapter 12: Cross sectoral perspectives

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Table of Contents

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), with a discussion presented on similarities and differences between the two approaches. {12.2}

Carbon Dioxide Removal (CDR) is an essential element of mitigation strategies to limit warming to 1.5°C–2°C by 2100 (*medium evidence, medium agreement*). It can be used to offset residual emissions to reach net-zero emissions and to return from temporary overshoots of carbon budgets or temperature thresholds by delivering net negative emissions (*robust evidence, high agreement*). {12.3, 12.7}

Direct air capture and carbon storage (DACCS), enhanced weathering and ocean-based approaches (including ocean alkalinity management and ocean fertilization) have moderate to large mitigation potential. The potential for DACCS is limited only by energy requirements and cost (200-600 US\$ tCO_2^{-1}; *medium evidence, medium agreement*). Enhanced weathering has the potential to remove <1 to ~100 Gt CO_2 yr^{-1}, at costs ranging from 24–578 US\$ tCO_2^{-1} (*medium evidence, medium agreement*). Ocean-based approaches have the potential to remove 1–100 $GtCO_2$ yr^{-1} at costs of 2 to 457 US\$ tCO_2^{-1} (*medium evidence, medium agreement*). {12.3}

Food systems, which currently contribute some [21-37%] to global greenhouse gas (GHG) emissions, are becoming increasingly carbon intensive, yet there is still wide-spread food insecurity and malnutrition. The full mitigation potential can only be realised when both supply and demand side opportunities are included, and all actors in the food system are involved *(robust evidence, high agreement*). {12.4}

Diets high in plant protein and low in meat, in particular red meat, are associated with lower GHG emissions. Studies show that a shift to diets with higher share of plant protein could lead to substantial reduction of GHG emissions 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 chain technologies promise substantial reduction in direct GHG emissions from food production. The full mitigation potential of such technologies can only be realised with low GHG energy systems *(limited evidence, high agreement).* {12.4}

The SR1.5 concludes that all assessed pathways that limit warming to 1.5°C require extensive land-based mitigation, with most including large total areas of 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}

A wide range of land-based mitigation options is available; mitigation value differs between the options, and is context-specific. Many land-related responses that contribute to climate change mitigation can simultaneously contribute to adaptation and combatting desertification and land degradation, enhance food security through increases in yields, and improve resilience through maintenance of the productivity of the land resource base. Careful integration of mitigation options with existing land uses helps to minimise trade-offs and maximise synergies (*medium evidence, high agreement*). {12.5}

Mitigation actions are commonly categorised by the sector in which they are applied, with some mitigation actions being applied in more than one sector. Examples of mitigation actions used in more than one sector include renewable energy technologies, carbon capture and storage (CCS) and fuel cells. Further areas where mitigation is considered from a cross-sectoral perspective are where a demand 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. {12.6.1}

Synergies and trade-offs resulting from mitigation policies are not clearly discernible from either the sector-specific studies nor the global and regional top-down studies literature but rather require a cross-sectoral integrated or multiple-objective-multiple-impact policy framework *(robust evidence, high agreement).* {12.6.2}

Carbon leakage is a critical cross-sectoral and cross-country outcome of differentiated climate policy. Ex post implementation literature continues to suggest low leakage rates, mostly due to specific aspects of implementation, however recent ex ante studies seem to indicate higher carbon leakage and associated industry competiveness effects even when compared to the earlier ex ante modelling studies of the IPCC AR5 report. Part of the later result is due to the spillovers related to the "green paradox", the effect that announcing future climate policies induces energy intensive countries and industries to increase production and use of fossil-fuels in the short term *(medium evidence, medium agreement*). {12.6.3}

Diversion of finance away from fossil fuels into renewables is an important channel for low-carbon transitions. Yet, Agriculture, forestry, and other forms of land use are also promising sectors for leveraging financing solutions to scale up GHG mitigation efforts beyond fossil fuel divestment *(medium evidence, high agreement*). {12.6.4}

New financing models and approaches are needed to leverage cross-sectoral synergies and manage trade-offs. The World Bank group and the International Finance Corporation have recently introduced an innovative approach named Result-Based Blended Finance addressing these issues *(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 prioritize 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}

12.1 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 emphasizes 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 an in-depth assessment of food systems, large-scale land-based mitigation and CDR technologies. Accordingly, the assessment in the chapter is structured around these two components with a number of sections synthesizing and summarizing cross-sectoral aspects of mitigation including potentials, technologies, synergies, and trade-offs while the other sections providing a focused assessment of GHG aspects related to emerging cross-sectoral issues such as CDR technologies, large scale land-based mitigation, and mitigation options related to food systems. While the former component is an update to the earlier IPCC assessments of these issues, the later component is a new contribution of the current IPCC cycle. As an overview of the scope and extent of the sectoral interlinks and crossovers related to mitigation potentials, cost, technologies, synergies, and trade-offs that are assessed in this chapter, Table 12.1 has been designed to provide a summary of the cross-sectoral interactions. 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

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 contribution of CDR technologies to GHG mitigation. The full cluster of technologies, practices, and approaches that remove and sequester carbon dioxide from the atmosphere, including land-based and non-land-based options, is considered. 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. GHG mitigation opportunities and related implications for sustainable development and adaptation are assessed including those arising from food production, landscaping, supply chain and distribution, circular economy, and diet shifts.

Section 12.5 covers impacts, risks and co-benefits that can be associated with land-based mitigation options, other than those that are inherent in the food system. Section 12.5 also covers land related impacts, risks and co-benefits associated with mitigation options that are commonly not designated land-based, but may still be associated with land occupation and consequent direct/indirect impacts. The section builds on the recent IPCC-SRCCL and considers implications for food security, biodiversity, and other ecosystem services. The section also investigates trade-offs and synergies related to the various uses of land and deployment strategies that can be implemented for achieving the scale of land-based mitigation that occur in pathways limiting global warming to 1.5°C or 2°C.

Section 12.6 provides a cross-sectoral perspective on mitigation co-benefits and trade-offs including those related to sustainable development and adaptation. The synthesized 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 competition among sectors for scarce resources. Policies that have direct sectoral effects include specific policies for reducing GHG emissions and non-climate policies that yield GHG reductions as co-benefits. Policies may also have indirect cross-sectoral effects, including synergies and trade-offs that may, in addition, spillover 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.

Table 12.1 Contribution from AR6 cross-cut group on sectoral interactions

	Ch05 Demand	Ch06 Energy	Ch07 AFOLU	Ch08 Urban	Ch09 Buildings	Ch10 Transport	Ch11 Industry	Ch12 x-Ch (land, CDR, food)
Ch05 Demand								
Ch06 Energy								
Ch07 AFOLU	diet, waste reduction urban sprawl, demand for wood leading to additional plantations	land-using E, bioenergy from waste streams and low quality wood, landless-fuels						
Ch08 Urban	circular-econ	E-dem / waste	urban ag nutrient recycling, city cooling by urban trees					
Ch09 Buildings	bldg/eff preference	energy eff /supply	woody biomass for heating, timber as building material	infra				

Ch10 Transport		EV / H_2 / liquids e-fuels	bioenergy, biofuel	urban trans system	EV infra			
Ch11 Industry	demand for materials and chemicals	ind process / H_2/ demand response	bioenergy biomaterial, biogenic CO_2 as feedstock for e.g. chemicals	urban planning, waste	appliances, bldg mtrls	component mfct. infrastructure needs		
Ch12 x-Ch (land, CDR, food)								

Note that each cell represents potential interactions (both one-way and two-ways) and the upper left cells are left blank. This table will be populated from contributions to be provided by sectoral chapters.

12.2 Aggregation of sectoral costs and potentials

12.2.1 Introduction

The term ‘mitigation potential’ is here used to report the quantity of reduced net emissions (sum of reduced emissions and/or enhanced sinks) of GHGs that can be achieved by a given mitigation option. The quantification is made based on a comparison with a baseline or reference case over a given period and the result is commonly expressed in CO_2-equivalents. The term ‘mitigation cost’ refers to the cost associated with realising a certain level of mitigation. The given cost per tonne (or ‘specific cost’) is usually within a range of monetary values, for example between x and y US$ per tonne of CO_2-equivalent (text adapted from Halsnæs et al. 2007). Different types of potentials exist, here we refer to the socio-economic (Sathanye et al. 2001) or techno-economic potential (Blok 2016). The monetary values can be defined as private or social specific costs. Private specific costs are based on market prices, while social specific costs reflect market prices, but also take externalities associated with the mitigation into consideration (text adapted from Halsnæs et al. 2007). In this section, we refer to social specific costs, which is obtained based on calculating of the costs of mitigation using a social discount rate, typically in the range of 4–10%.

Costs and potentials for the year 2030 have been presented earlier, notably in the 4th Assessment Report of the IPCC (Barker et al. 2007) and the Emissions Gap Report (UNEP 2017). In addition, McKinsey (2009) presents a marginal-abatement-cost curve for 2030, which also represents costs and potentials.

Chapters 5–7 and 9–11 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, which makes it useful to provide an aggregate of the sectoral results (in Section 12.2.2 for 2030 and in Section 12.2.3 for 2050). In this aggregation, we will correct for interactions and overlap as much as possible. However, such systemic effects are more rigorously taken into account in IAMs. We will make a comparison between the sectoral results and the outcomes of the IAMs in Section 12.2.4.

For the medium term (the year 2030), the results will be presented similarly as in AR4, with a breakdown of the potential in cost bins. For the year 2050, a more qualitative approach will be provided, indicating the relative importance of options for each of the sectors. Costs will also be presented in an indicative way for the year 2050.

Below, emission reduction potentials are presented based on comparison with a baseline scenario. Unfortunately, not all costs and potentials are determined against the same baseline. Two often used scenarios are the SSP-2 scenario (IIASA 2018) and the Current Policies scenario from the World Energy Outlook (IEA 2018). 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, see Table 12.2.

Table 12.2 Key characteristics of two scenarios used as baselines for determining costs and potentials. The values are estimations for the year 2030 (IEA 2018; IIASA 2018).

	SSP2-4.5 (MESSAGE-GLOBIOM)	WEO* (Current Policies)	CP vs. SSP2
Real GDP (PPP) $ 2017 compound average annual growth rate (%) 2017–2040		3.4	
Real GDP (PPP) (billion US$ 2017 yr^{-1})	179471	197164	+10%
Real GDP (PPP) (billion US$ 2005 yr^{-1})	143019	157118	+10%
Population compound average annual growth rate (%) 2017–2040		0.9	
Population (million)	8262	8412	+2%
Total primary energy use (EJ yr^{-1})	645	709	+10%
Total final energy use (EJ yr^{-1})	509	499	-2%
Energy-related CO_2 emissions (MtCO_2 yr^{-1})		37748	
CO_2 emissions fossil fuels and industry (unharmonised) (MtCO_2 yr^{-1})	39797	40048	+1%

*) Will be updated to WEO 2019 in Second Order Draft

12.2.2 Aggregate costs and potentials for 2030

An overview of emission reduction potentials for different mitigation options is presented in Table 12.3, based on the analyses made in Chapters 5–7 and Chapters 9–11. Some of the options influence each other or are mutually exclusive, so the numbers for individual mitigation actions cannot be aggregated. However, a high-level overview of mitigation potentials in the different cost categories was developed for the main sectors, see Table 12.4. To correct for different baselines and for overlap and interaction between options, several adjustments were necessary. The most important ones are: (Placeholder - *to be added in Second Order Draft*):

- …
- …
- …

(Will include all quantitative details in Appendix in the Second Order Draft)

The resulting estimated total emission reduction potential for 2030 corresponds to … GtCO_2-eq, which represents ... - …% of the emissions in the baseline. If all the emission reduction options would be implemented, this would lead to an emission reduction, compared to the current (=201x) level, of … - …%.

[Regional detail / variation]

A number of comments should be made with respect to these numbers [disclaimers / major uncertainties / knowledge gaps].

- …
- …

Table 12.3 Detailed overview of GHG emission reduction potentials ($GtCO_2$-eq) in the various cost categories

Emission reduction options per sector	Cost categories (US$ $tCO_2\text{-eq}^{-1}$)				
	<0	0–20	20–50	50–100	100–200
Energy systems					
Wind energy					
Solar energy					
Nuclear energy					
CCS					
Bioenergy					
BECCS					
Other					
Agriculture, forestry and other land use *					
Reducing deforestation, af/reforestation, etc.		3.5	0.1	5.6	11.5**
Changed agricultural practices (excl. soil sequestration)		0.4	0.0	0.7	5.0**
Soil sequestration		2.0	0.1	2.0	6.9**
Food supply chain management					0.7***
Demand management					2.6 – 14.4***
Cross-cutting and miscellaneous		0.8	0.0	0.5	4.2
Buildings					
Efficient new buildings					
Retrofit existing buildings					
Efficient lighting					
Efficient appliances					
Other					
Transport					
Light duty vehicles – battery-electric					
Light duty vehicles – fuel cells					
Heavy duty vehicles – battery-electric					
Heavy duty vehicles – fuel cells					
Marine – energy efficiency					
Aviation – energy efficiency					
Modal split changes and demand reduction					
Other					
*Industry*****					
Steel – material efficiency			0.6		
Steel - energy efficiency		0.3			
Steel - enhanced recycling			0.4		
Steel - fuel switching			0.2		
Steel – new production routes incl. H_2 and CCUS			n.a.		
Cement – material efficiency			0.3		
Cement – material substitution			0.3		
Cement – energy efficiency		0.2			
Cement – fuel switching			0.3		
Cement CCUS			n.a.		
Non-sectoral					
Direct air capture					
Enhanced weathering					

Other

Note that potentials cannot be aggregated, as they may be mutually exclusive.

*) Potentials in this category are rather averages for the period 2030– 050 than for specifically for the year 2030. Uncertainty ranges are substantial, typically +/- 50%, sometimes even higher.

**) Part of the this potential may have costs higher than 200 US$ tCO_2-eq^{-1}

***) Cost categories unknown

****) More sectors to be added

(To be completed in Second Order Draft)

Table 12.4 Overview of aggregate sectoral GHG emission reduction potentials in the various cost categories

Sector	Cost categories (US$ tCO_2-eq^{-1})				
	<0	0–20	20–50	50–100	100–200
Energy sector					
Agriculture, forestry and other land use					
Buildings					
Transport					
Industry					
Non-sectoral					
Overlap correction					
Total of all sectors					

(To be updated in next draft)

12.2.3 Sectoral findings on emission pathways until 2050

As noted before, the results for 2050 will be presented with less quantitative details. The sectoral results are summarised in Table 12.5.

Table 12.5 Emission reduction options and their characteristics for 2050

Sector	Major options	Complementary and alternative options	Sector interac tions	Specific costs*	Degree to which zero-GHG is possible
Energy sector					
Agriculture, forestry and other land use					
Buildings					
Transport					
Industry	Material efficiency Recycling (steel) Materials substitution (cement) Direct reduction with hydrogen, electrolysis (steel) CCS	Energy efficiency Fuel switching		Intermediate	Approx. 85% reduction is feasible. Net-zero is possible with retrofitting and early retirement
Non-sectoral					

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

12.2.4 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). For FOD, we use the IPCC AR6 scenario database. The emissions reductions take place across sectors, although the response of the AFOLU sector is somewhat ambiguous (Figure 12.1 for 2030 and Figure 12.2 for 2050). A significant portion of emissions reduction takes place in the energy conversion sector (shown as "energy supply").

The emission reductions for agriculture, forestry and other land use found by the IAMs are typically in the range of 0–5 $GtCO_2$-eq, substantially lower than the potentials found in the sectoral assessment (Table 12.3). *(Explanation for the difference and comparisons for other sectors to be added.)*

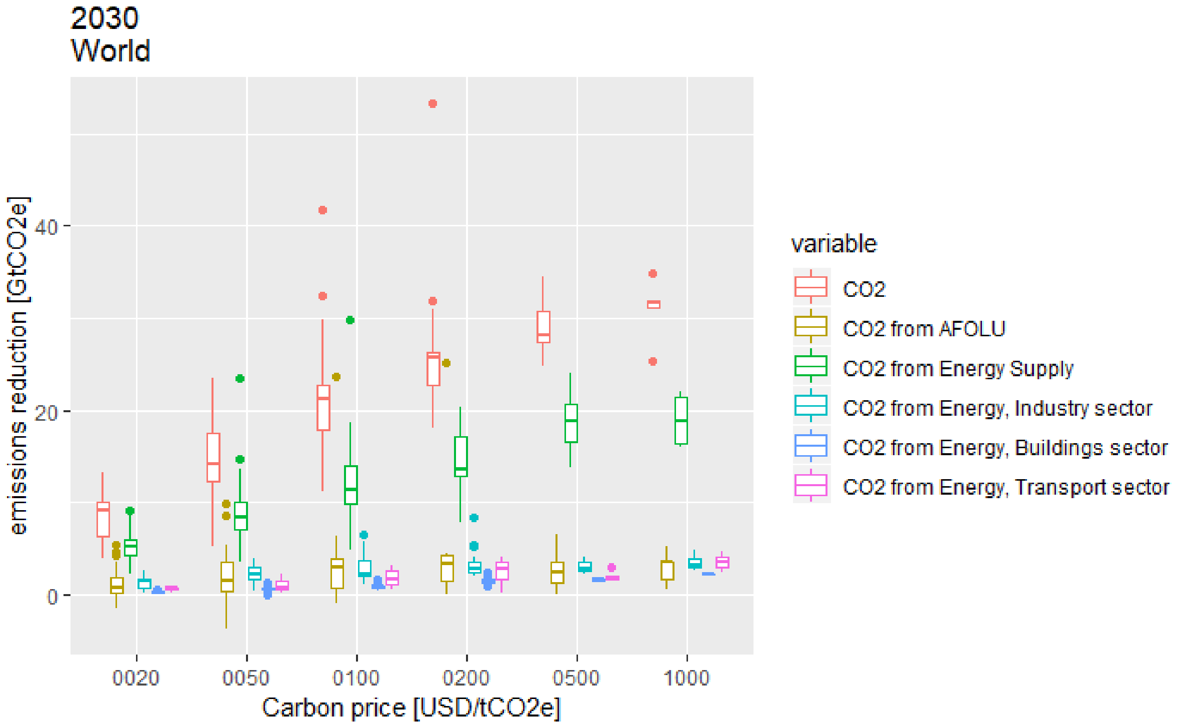

Figure 12.1 Box plot of global emissions reduction for each sector (colour) at different carbon price levels (horizontal axis) for 2030, based on the IPCC AR6 scenario database (https://data.ene.iiasa.ac.at/ar6-scenario-submission/). Outliers of each box plot are represented as dots.

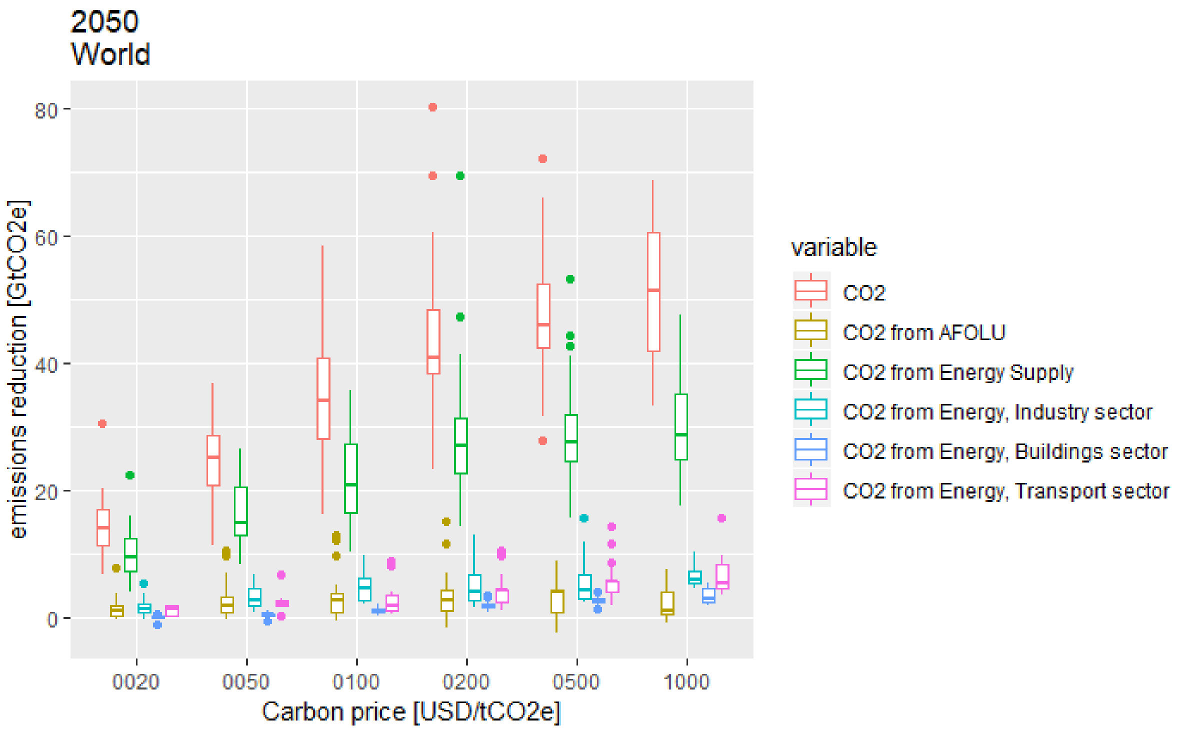

Figure 12.2 Box plot of global emissions reduction for each sector (colour) at different carbon price levels (horizontal axis) for 2050, based on the IPCC AR6 scenario database (https://data.ene.iiasa.ac.at/ar6-scenario-submission/). Outliers of each box plot are represented as dots.

(The figures above will be compared in text/tables to the information provided in Section 12.2.2 and 12.2.3, discussing similarities, differences and the implications.)

12.3 CO_2 removal (CDR) options (and GHG removal)

CDR refers to a cluster of technologies, practices, and approaches that remove and sequester carbon dioxide from the atmosphere. Despite the common feature of removing carbon dioxide, these technologies can be very different (Smith et al. 2017). One can usefully distinguish between natural and technological options, and a combination of both. In general, natural CDR options are less costly, closer to deployment but more vulnerable to reversal, whereas the technological CDR options have higher costs, higher research, development & demonstration (RD&D) needs but the advantage of more permanent CO_2 storage, first and foremost in geological reservoirs (Figure 12.3).

A number of CDR options (e.g., A/R, BECCS, soil carbon sequestration, biochar, wetland / peatland restoration and coastal restoration) are dealt with elsewhere in this volume (Section 12.5, Chapter 7). These options are synthesised in Section 12.3.3. Others, not dealt with elsewhere, i.e., DACCS, enhanced weathering of minerals and ocean-based approaches including ocean fertilization and alkalinity enhancement, are discussed in Sections 12.3.2.1 to 12.3.2.3 below.

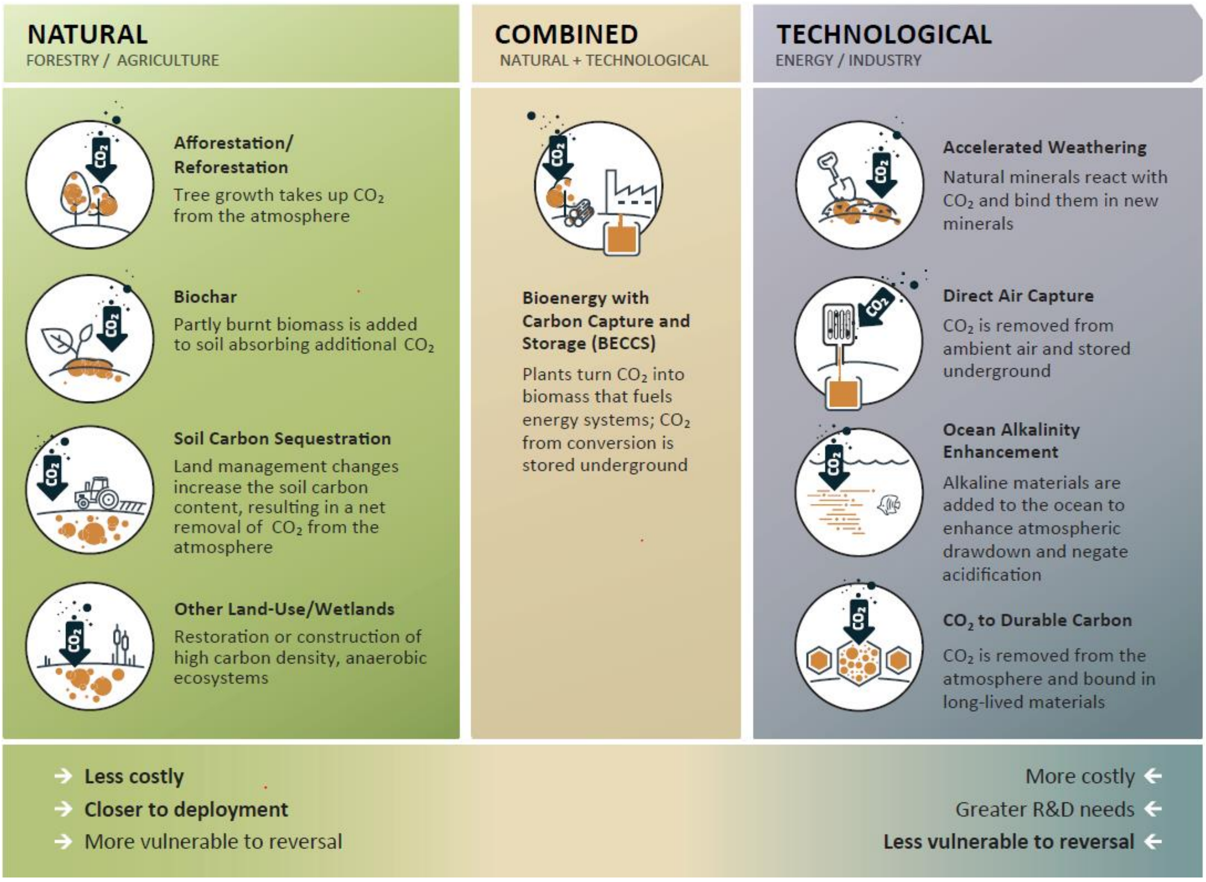

Figure 12.3. Main options for carbon dioxide removal [original figure from Chapter 7 of UNEP Emissions Gap Report 2017 (Smith et al. 2017), for SOD, terminology will be changed to exactly represent categories and methods dealt with in this section, e.g. "land-based" instead of "natural" or "enhanced weathering" instead of "accelerated weathering".]

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 quickly return from temporary overshoots of carbon budgets or 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 national and sub-national governments have included A/R into their overall mitigation portfolios, none is pursuing a comprehensive CDR strategy so far (Peters and Geden 2017; Fridahl 2017). There is concern that the prospect of large-scale CDR could obstruct conventional mitigation efforts (Markusson et al. 2018), might lead to an overreliance on technologies that are still in their infancy (Anderson and Peters 2016), could overburden future generations (Shue 2018) or might be perceived negatively by broader publics (Royal Society and Royal Academy of Engineering 2018).

Some biological practices used for CDR (like A/R, wetland restoration and soil-carbon management) have been practiced for decades to millennia. Conversely, for a few of the engineering-based approaches such as DACCS and BECCS, experience is limited, with only a few plants in operation (Smith et al. 2017). Given long time periods involved in scaling up and deploying novel technologies, there are huge challenges to be tackled in research, development and demonstration in order to advance innovation 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). In scenarios compatible with limiting the temperature increase to below 2°C by the end of the century, annual BECCS CDR deployment reaches 0.06 $GtCO_2$ yr^{-1} by 2030, 3.3 $GtCO_2$ yr^{-1} by 2050 and 10.6 $GtCO_2$ yr^{-1} by 2100 (values are the medians), and AFOLU CDR 0.0 $GtCO_2$ yr^{-1}, 1.9 $GtCO_2$ yr^{-1}, and 2.4 $GtCO_2$ yr^{-1} for these years. Cumulative volumes of BECCS CDR and AFOLU CDR reach 403.6 $GtCO_2$ and 175.8 $GtCO_2$ by 2100, respectively. Depending on assumptions on residual emissions, gross cumulative CDR volumes of 149.3 $GtCO_2$ are needed to reach a balance between emissions and removals for reaching net-zero in 2069 (values are the medians and based on the AR6 scenario database).

While many techniques are 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) but they remain an exception. 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 AFOLU has been analysed, but compared with other types of analyses, there is little assessment of the role of other CDR in national/regional policies, with some exceptions (e.g., Sanchez et al. 2018 and Patrizio et al. 2018 on BECCS in the US; Larsen et al. 2019 on DAC in the US; Daggash et al. 2018 on BECCS and DACCS in the UK; Kato and Kurosawa 2019 on BECCS in Japan; Kraxner et al. 2014 on BECCS in South Korea; Breyer et al. 2019 in the Maghreb region).

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 uses chemical bonding to remove dilute CO_2 directly from ambient air and then store it. 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) absorption or adsorption on a liquid or solid sorbent, c) regeneration of the sorbent with heat, moisture and/or pressure. After capture, the CO_2 stream can be stored underground or utilised. Only permanent storage (either in geological reservoirs or through mineralization) can result in net removal of CO_2 from the atmosphere. The efficiency of CO_2 removal depends on the carbon intensity of the energy input (electricity and heat). Utilization of captured CO_2 to produce synthetic fuels, building materials or plastics will only have a temporary 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).

DAC 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 (Carbon Engineering) and solid sorbents with heat regeneration (Climeworks and Global Thermostat) (National Academies of Sciences 2019). These projects are supported by public RD&D funding or sometimes serve for utilization niche markets (e.g., enhanced oil recovery, CO_2 for beverages or greenhouses). As of March 2019, there are 11 plants worldwide, whose scale is ~1 $ktCO_2$ yr^{-1}, with the largest designed to capture 4 $ktCO_2$ yr^{-1} in Alabama, USA (National Academies of Sciences 2019; Larsen et al. 2019). 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 2019). For instance, the air contactor of Carbon Engineering takes a cross-flow configuration, not the counter-current configuration often used in conventional CCS (Keith et al. 2018; National Academies of Sciences 2019). An RD&D program dedicated to DAC would therefore be required (National Academies of Sciences 2019; Larsen et al. 2019). Possible basic research topics include development of new liquid solvents, novel solid sorbents, and novel equipment or system designs (National Academies of Sciences 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 (~400ppm) from the ambient air, it is less efficient and more costly than conventional CCS applied to power plants and industrial installations (with a CO_2 concentration of ~10%). The cost of a liquid solvent system is dominated by the energy cost (because of the much higher energy demand for CO_2 regeneration) 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 US\$ 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 US\$ 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 US\$ tCO_2^{-1} (Sinha et al. 2017; Keith et al. 2018; National Academies of Sciences 2019).

Potentials: There is no specific study on the potential of DACCS but the literature has assumed that the potential of DACCS is virtually unlimited (Marcucci et al. 2017; Fuss et al. 2018) since DACCS encounters less non-cost constraints than any other CDR option. 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 are 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 50–100 EJ yr^{-1} of energy consumption, which can be contrasted with the current primary energy supply of ~500 EJ yr^{-1}. 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 Climeworks' technology (Fasihi 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). 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).

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. Because of its very high demand for low-carbon heat and power, DACCS would compete with more basic energy needs and could therefore negatively affect SDG 7 (*Affordable and Clean Energy*).

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, (Larsen et al. 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.

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 elsewhere) so that they absorb atmospheric CO_2 (Schuiling and Krijgsman 2006; Hartmann et al. 2013; Beerling et al. 2018). 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 2008a), 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 2008a), 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. 2019a).

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 US$ tCO_2^{-1} to 3460 US$ 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 US$ 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 US$ 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). Potential co-benefits and trade-offs associated with enhanced weathering are discussed further below.

Co-benefits: Enhanced weathering could enhance soil carbon sequestration and protect against soil erosion and can improve plant growth by pH modification and by supplying minerals (Baldock and Skjemstad 2000; Yu et al. 2017; Guntzer et al. 2012; Tubana et al. 2016; Manning 2010; Smith et al. 2019a; Haque et al. 2019). In terms of improving soil functions, weathering of silicate minerals in soils increases the cation exchange capacity resulting in increased nutrient retention and availability (Gillman 1980; Gillman et al. 2001). This could also stimulate organic carbon input from roots and symbiotic mycorrhizal fungi (Beerling et al. 2018), leading to stabilisation in soil aggregate formation (Wrigth and Upadhyaya 1998), and the interaction between organic carbon and minerals, which ultimately improves ‘soil quality’ (Baldock and Skjemstad 2000) and reduces erosion rates (Beerling et al. 2018). Production of alkalinity by chemical weathering aids reversal of soil acidification which in turn improves crop nutrient uptake and yields. Silicic acid formation following weathering is readily taken up by plants and can increase resistance to pests and diseases (Beerling et al. 2018). Some rocks contain elevated concentration of potassium, phosphorus, and silicon, and may also be an alternative source of nutrients for supporting agricultural production (Kantola et al. 2017; Beerling et al. 2018), and elevated concentrations of trace elements can support human nutrition (Shewry et al. 2016) and crop production (Guntzer et al. 2012). Harvesting removes nutrients from the soil resulting in their gradual depletion (e.g. Tubana et al. 2016). Experiments testing the impact of crushed rock addition to plant growth trials have variable results, with some experiments demonstrating increased mobilisation, uptake, or yield (Manning 2010).

Enhanced weathering could contribute positively to the delivery of a number of ecosystem services (Smith et al. 2019a). For example, enhanced weathering could benefit the regulation of ocean acidification, since the dissolution of silicate minerals applied to the land consumes acidity and creates drainage waters with slightly elevated alkalinity, which may ameliorate ocean acidification once they reach the ocean (Taylor et al. 2016)(see also Section 12.3.2.3). It could help the regulation of freshwater quantity, flow and timing by increasing the organic carbon content of soils (e.g. through organo-clay aggregate formation; (Yu et al. 2017)) to improve soil water retention (Rawls et al. 2003), and may thereby reduce the amount of additional water needed for irrigation of croplands (Smith et al. 2019a). Stabilising and maintaining soils, particularly those that are exposed to the risk of erosion, may improve water retention and limit the impact of flooding (Pimentel et al. 1995). Accelerating the weathering of minerals in soils may lead to the formation of clay, and mineral organic aggregates, thus replenishing the material lost through erosion and increasing the cation exchange capacity of rebuilt soils (Beerling et al. 2018), thus contributing to the formation, protection and decontamination of soils and sediments.

Enhanced weathering could contribute positively to the delivery of a number of the SDGs (Smith et al. 2019a). For *No Poverty*, the supply chain associated with mineral addition to the land surface may provide local economic growth through mineral extraction, processing, and transport. However, the mining industry has a poor track record for alleviating local poverty (Pegg 2006). For *Zero Hunger* enhanced weathering may provide benefits by supplying plant growth limiting nutrients, reversing soil acidification, restoring plant-available silica pools, increasing soil cation exchange capacity and augmenting pest resistance which could all increase crop yields (Beerling et al. 2018). Further, since the cost of mineral fertilisers limits their application in some areas, enhanced weathering could improve societal access and increase yields (Manning 2008b; Amundson et al. 2015). For *Clean water and sanitation*, the primary benefit is a potential decrease in water requirements for cropland irrigation. However, water is used in mineral aggregate extraction (e.g. dust suppression Grundnig et al. 2006), which can impact local flows of freshwater in streams and groundwater (Younger and Wolkersdorfer 2004). For *Responsible consumption and production*, since amending agricultural soils with crushed silicate rocks improves yields, it can potentially reduce consumption of rock-derived fertilisers that represent a finite resource. Further, by reversing soil acidification, enhanced weathering offers an opportunity for reducing calcium carbonate production for liming operations (West and McBride 2005). For *Climate action*, the CDR potentials are presented above, but there may also be interactions with other CDR strategies, e.g. increasing productivity of plants grown as feedstock for biochar or BECCS, A/R, but these interactions require field-scale demonstration and assessment (Royal Society and Royal Academy of Engineering 2018). Helping neutralise soil acidification of croplands linked to application of nitrogenous fertilisers can also reduce soil CO_2 efflux. For *Life below water*, enhanced weathering could promote the flow of elevated alkalinity freshwater to coastal environments and the ocean, which may mitigate the impacts of ocean acidification and reduce associated impacts on corals and fisheries (Taylor et al. 2016). Increasing silica concentrations in run off into coastal oceans can favour the growth of diatoms over problematic non-siliceous algae (Beerling et al. 2018). For *Life on land*, existing agricultural lands could be made more productive through enhanced weathering, which could lead to land sparing by reducing land demand for croplands, which could decrease pressure on biodiversity (Amundson et al. 2015).

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 decarbonised power.

Role in mitigation pathways: Work to include enhanced weathering in integrated assessment models, used to explore mitigation pathways, is underway, but as yet, no assessments of enhanced weathering in mitigation pathways have been undertaken. Other estimates of global potential have been made (see paragraph “Potentials” above).

12.3.2.3 Ocean-based approaches (fertilization and alkalinity enhancement)

The ocean, as part of the earth's climate system, plays an important role in climate regulation and is also vulnerable to the effects of climate change – temperature rise, acidification increase, sea level rise, etc. 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). On long-timescales (~100–200 ka) the ocean and weathering will reduce atmospheric CO_2 to values close to pre-industrial (Lord et al. 2016). The ocean is 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. Assessment of the wide range of proposed marine geoengineering (GESAMP 2019) catalogued six CDR approaches. Most studied are ocean fertilization and alkalinity enhancement. Other approaches include carbon storage in the ocean, ocean pumping (or enhanced upwelling), methane capture and destruction. Sequestration of CO_2 by shallow coastal ecosystems, also referred to as "blue carbon", can be considered an ocean based CDR approach.

Ocean fertilization (OF). The natural mechanism of carbon transfer from the atmosphere to the deep ocean – 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 take up 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 oceans 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 fertilization for fish stock enhancement. Iron fertilization is best studied to date, but knowledge so far is still inadequate to predict global consequences.

Ocean Alkalinity (OA). Storage of CO_2 by increasing ocean alkalinity ('ocean alkalinity enhancement' or 'artificial ocean alkalinisation') requires the extraction, processing, and dissolution of minerals (Renforth and Henderson 2017). Enhanced weathering (Section 12.3.2.2) in which the dissolution products are conveyed to the ocean, is one such method. This results 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 "blue carbon" was introduced in 2009 by the United Nations Environment Programme. The term refers to the carbon sequestered in coastal ecosystems such as mangroves, sea grasses and salt marshes. More than 50% of the carbon dioxide absorbed by plants on Earth circulates into the ocean and more than half of that carbon is absorbed by shallow coastal ecosystems, which account for only 0.5% or less of the total ocean area (Hori et al. 2019).

Status: The iron fertilization method has a natural analogue. It has been noted that the periods of glaciation in the geological past are associated with changes in the dust removal 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 the method is confirmed by a number of field experiments conducted in different areas of the ocean (Trull et al. 2015; Williamson et al. 2012).

Technologies for increasing ocean alkalinity 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 proposed the creation of highly reactive lime that would readily dissolve in the surface ocean and sequester CO_2. An alternative proposal was developed independently by Rau and Caldeira (1999), who suggested that the dissolution of carbonate minerals (e.g., $CaCO_3$) exposed to waste flue gas CO_2 and seawater as a means for increasing ocean alkalinity. 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, G.; Widdicombe, S; Spicer, J. I; Findlay 2013; Gore et al. 2018) and a constrained field study (Albright et al. 2016)

In recent years, there has been increasing research and scientific publishing on the potential, effectiveness, risks, and possibility of introducing CO_2 sequestration in shallow coastal ecosystems. This may be due to that about 20% of the countries that have endorsed the Paris Agreement have committed themselves, as part of their Nationally Determined Contributions (NDCs), to blue carbon approaches as a climate change mitigation option and are moving toward measuring blue carbon 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 ocean fertilization, 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, the experiments have shown that the real efficiency of the method can be much lower, because when oxidation to CO_2 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 implication both for the success of this strategy, and its cost. Estimates of various authors show that the potentially achievable rate net absorption of CO_2 may be between 1–3 $GgCO_2$ yr^{-1}, the cumulative absorption by the end of the century will be 100–300 $GgCO_2$. (Ryaboshapko and Revokatova 2015; Minx et al. 2018).

For ocean alkalinity, the ocean has the capacity to store hundreds to 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 ability 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). However, there it is not evident that seaweed culturing would extremely offset global agriculture. Offsetting agriculture appears more feasible at a regional level, especially areas with strong climate policy.

Potential co-benefits and adverse effects: Co-benefits for ocean fertilization include increased productivity and fisheries, reduced upper ocean acidification. Drawbacks include subsurface ocean acidification, deoxygenation; altered regional meridional nutrient supply, fundamental alternation of food webs (GESAMP 2019). Potential increase in fish catches; enhanced biological production (Minx et al. 2018).

For ocean alkalinity, 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 relative sensitivity of species to changes in alkalinity, its use for mitigating the effects of ocean acidification in natural environments requires careful consideration. 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.

Risks and impacts: For ocean fertilization, the emergence of stocks of potential toxic species of diatoms during the development of several of the mesoscale iron enrichment experiments (Silver et al. 2010; Trick et al. 2010). There is also limited evidence of increased concentrations of other GHG's such as methane and nitrous oxide during the subsurface decomposition of the sinking particles from iron stimulated blooms (Law 2008). Unknown impacts on marine biology and food web structure; changes to nutrient balance; anoxia in surface ocean; probable enhanced production of N_2O and CH_4 (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 ocean Alkalinity, the impact of increasing alkalinity on ocean chemistry depends 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) being supplied to ocean ecosystems (Montserrat et al. 2017), the ecological consequences of this remain poorly understood (Meysman and Montserrat 2017).

For "blue carbon", the potential risks relate to the high sensitivity of coastal ecosystems to external impacts associated with both degradation and attempts to increase carbon sequestration. Damage coastal ecosystems may reduce their resilience in the long-term, leading to a reversal of carbon sequestration. Political aspects are associated with the climate sequestration component of coastal ecosystems within a mitigation context because it is very difficult to determine which emissions and removals are natural and which are anthropogenic. Also there are concerns that this may dilute mitigation ambition in other sectors.

Costs: Ocean fertilization costs depend on nutrient production and its delivery to the application area (Jones 2014). The costs range from 2 US\$ tCO_2^{-1} (Boyd 2008; Denman 2008) to 457 US\$ tCO_2^{-1} (Harrison 2013). A detailed economic analyses for macronutrient application reports 20 US\$ tCO_2^{-1} (Jones 2014), whereas (Harrison 2013) details that costs are much higher due to the overestimation of sequestration capacity and underestimation of logistic costs. Cost of ocean fertilization method ranges are between 50–500 US\$ tCO_2^{-1} (Minx et al. 2018).

Techno-economic assessments of ocean alkalinity largely focus on deriving overall energy and carbon balances and there has been little optimization or comprehensive life cycle assessment. Cost ranges are between 40–260 US\$ 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 US\$ 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 cost on the order of 100–160 US\$ tCO_2^{-1}.

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 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 technical and socio-economic potential 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. 2019b; Hurlbert et al. 2019; Mbow et al. 2019; Olsson et al. 2019).

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 stabilization, 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. 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 carbonization 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 sustainable concerns (Fuss et al. 2018).

Costs: Costs across technologies vary significantly (Smith et al. 2016) and are estimated for BECCS as 15–400 US\$ tCO_2^{-1}, A/R 0–240 US\$ tCO_2^{-1}, soil carbon sequestration- 45–100 US\$ tCO_2^{-1} and biochar-10–345 US\$ 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. 2019) (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. 2019b; 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).

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).

A/R is the among 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, but there is potential for achieving co-benefits. 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).

12.4 Food systems

12.4.1 Introduction

Food and nutrition are one of the fundamental human needs. Food needs to be grown and processed, if food in sufficient quantity and quality is not available locally, transported and distributed, and finally prepared. Traditional food systems involve only few people and short supply chains. Modern food systems are 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 diets and food consumption patterns of the population, productivity, profit and livelihood of food producers and other actors in food value chains, but also the impact on the environment (Zurek et al. 2018).

While food insecurity affects more than 820 million people and in 2018 and was increasing for the third year in a row with the prevalence of undernourishment at 10.8%, two billion adults are overweight or obese, with an upward trend globally (FAO et al. 2019). In the last century, development of the global food system was driven by providing affordable calories and reducing food insecurity. As a consequence, total factor productivity increased while calories supply concentrated on few crops (Benton and Bailey 2019). Even though the global food system produces sufficient calories for the world population, there is a lack of nutrient-dense foods such as fruit and vegetables (Berners-Lee et al. 2018; Kc et al. 2018). 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)*. One third of children under 5 years suffer from stunting, wasting or overweight, and even more experience lack of vitamins or other essential nutrients (UNICEF 2019). The current global food system has severe consequences not only to individual's wellbeing, but also to national health insurance and infrastructure systems, and causes economic losses for example through reduced working efficiency (Benton and Bailey 2019) *(medium evidence, high agreement)*.

[Placeholder - To be added for SOD: text on food safety. Anti-microbial resistance, GMO, antibiotics, pesticides, animal epidemics (food scares like swine fever, avian influenza, BSE).]

Modern food systems are characterized by increasing vertical and horizontal integration, with increasing trade of high-value products and multinational companies contracting agricultural suppliers for corporate values chains (Swinnen and Maertens 2007; Folke et al. 2019). This might lead to an asymmetric distribution of the potential to influence food value chains and transform the food systems. Higher influence is concentrated in the post-farm gate food supply chain (e.g. food processors and retailers downstream of the farm gate), in contrast to the distribution of GHG emissions that are dominated at the food production stage, with governmental intervention being required to enhance enabling or reduce constraining conditions (see Figure 12.4).

The global food system today employs 27% of working people in agriculture, fisheries, and forestry, a number that is decreasing in all countries, between 1995 and 2016 from 6% to 3% in developed countries and from 76% to 67% in developing countries (World Bank 2019). The share of persons employed in the food industry and service sectors differs between different food systems. In traditional food systems (e.g., Sub-Saharan Africa), ca. 10% of people are employed in the food industry and service sector, while 90% work in the farming sector. In food systems in transition (e.g. Brazil), about 50% of people are employed in the farming sector, and in modern food systems (e.g. U.S.), about 80% of persons work in the food industry and service sectors, with only about 20% in the farming sector (Townsend et al. 2017).

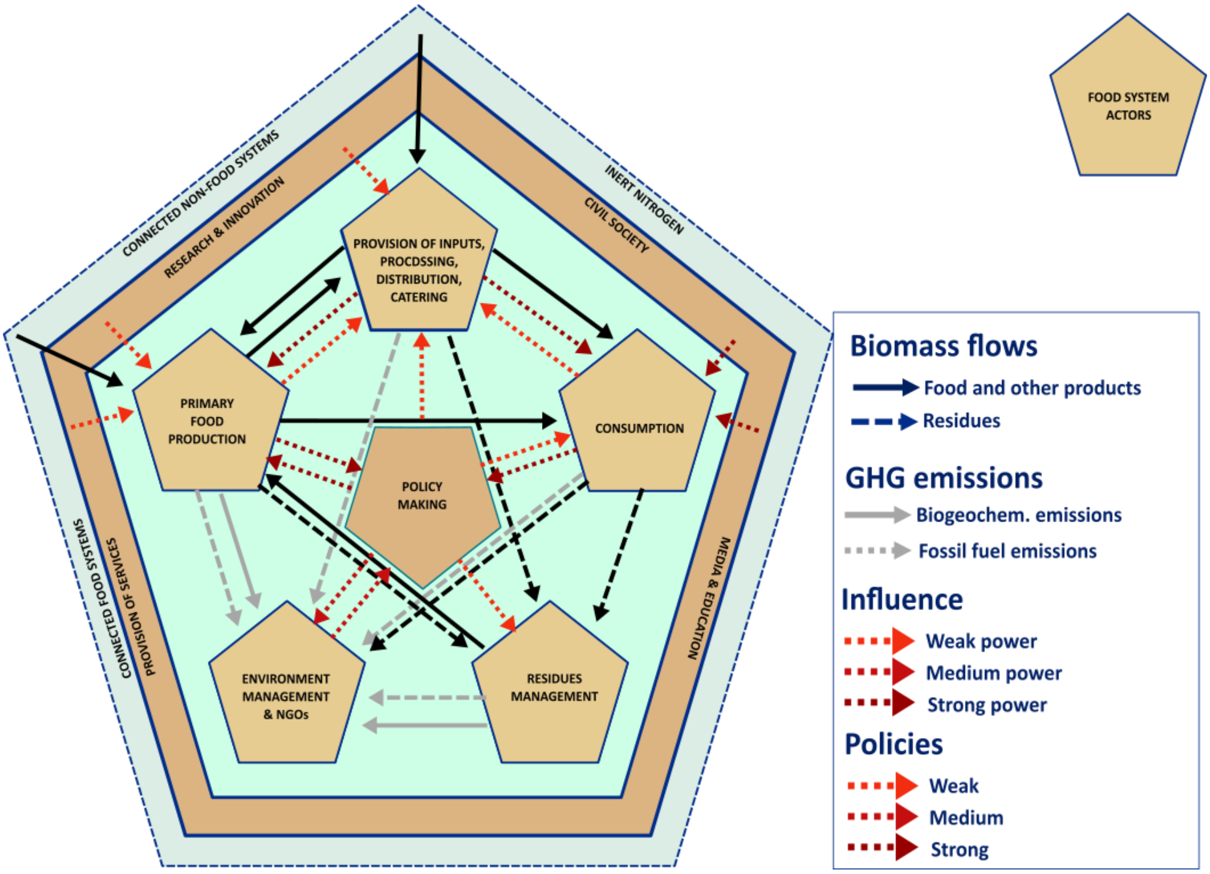

Figure 12.4 Schematic representation of the current global food system, showing sources of GHG emissions from biogeochemical processes and energy consumption, distribution of influences between food system actors, and influence of policy making. Food system actors include food producers, food consumers, food supply chain actors, residues managers, and managers of environmental losses; 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.

Food supply chain actors exert influence both to food producers through supply contracts and to food consumers by shaping the external food environment. Food producers, consumers and environmental NGOs have little direct influence on the food supply chain, but are able to influence policy making. The internal food environment civil society trends and information obtained through media or education.

Research and Innovation can enhance technological progress, supported by advisory and other service systems.

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. The figure indicates the asymmetry in the global food system that exists between the distribution of GHG emissions sources and the distribution of influence.

12.4.2 GHG emissions from food systems

12.4.2.1 Food systems in the Special Report of Land and Climate Change

The chapter on food security of the IPCC Special Report on Climate Change and Land (2019) goes beyond the traditional approach that evaluates food systems from a perspective centred in production systems and disaggregated sub-sectors. It rather brings a holistic approach to evaluate food systems, in which all activities and actors in the production, transport, processing, retailing, storage, consumption, and food waste are evaluated as a whole (Mbow et al. 2019). This full food system approach recognises that the food supply and demand systems are intrinsically interlinked. These complex connections between small- and large-scale farmers, food consumers (including dietary choices) were assessed, recognising the need to a broader engagement of all food actors (Rosenzweig et al. 2020). Following this approach, the food system contribution to global GHG emissions includes not only the traditional agriculture and food-related land use change emissions, but also the food supply chain (energy use, transport and food industry) emissions. The overall global anthropogenic emissions from the food systems vary between 10.8 and 19.1 $GtCO_2$-eq yr^{-1}, equivalent to 21–37% of total anthropogenic emissions. This is significantly larger than the traditional agriculture and food-related land use change emissions (Table 12.6Table 12.6).

Table 12.6 Comparison of 2007-2016 mean values and standard deviations of emissions from global food systems GHG emissions by component (Rosenzweig et al. 2020; IPCC 2019)

Food system Components	Emissions ($GtCO_2$-eq yr^{-1})	Percentage of anthropogenic GHG emissions (%)
Agriculture	6.2 ± 1.4	10–14
Food-related FOLU	4.9 ± 2.5	5–14
Pre- to post-production	2.6–5.2	5–10
Total	10.8–19.1	21–37

The food system approach allows designing more interconnected climate policy responses to tackle climate change from producer and consumer lens. The SRCCL found that the technical mitigation potential supply- and demand-side responses are fairly comparable and equivalent to 3.0–17.6 $GtCO_2eq$ yr^{-1}. This shows that mitigation actions need to go beyond food producers and suppliers to incorporate dietary changes and consumers’ behavioural patterns. This reveals that producers and consumers need to be hand-in-hand to reduce GHG emissions.

The report also identified that over one third of all food produced globally is either lost or wasted. Its GHG emissions were estimated as 8–10% of total GHG emissions. Therefore, reducing food loss and waste is an important GHG mitigation measure.

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.

The IPCC SRCCL Food Security chapter identified three major knowledge gaps:

- Development of a food system emission inventory (disaggregation of GHG emissions from food industry and transportation is not well characterised);
- Dynamics of dietary change (behavioural patterns and interaction with human health and nutrition of healthy and sustainable diets and associated feedbacks are not well understood);
- Instruments and mechanisms to accelerate transitions towards sustainable and healthy food systems (role of economic incentives to more sustainable agricultural practices, how to overcome barriers to implementation, accelerate plant-based dietary, etc).

12.4.2.2 Sectorial contribution of GHG emissions from food systems

All sectors contribute to food systems' GHG emissions. In 2015, 24% of all anthropogenic emission (excluding LULUCF) are associated with the production, processing, distribution or consumption of food (Crippa et al. 2019). The largest contribution of 50% food systems' emissions is from the agriculture sector (see Chapter 7), followed by the use of energy (25%), waste management (14%), and industrial processes (5.8%). The share of the food supply chain to total food systems emissions is therefore 50% or 42% if waste management is not taken into account. *(Ranges will be added in SOD.)*

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

Refrigeration is the main single use of energy in the retail / supermarket sector with estimated 43% (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). Data show substantial reduction of losses of perishable food in countries with high penetration of cold chains (James and James 2010).

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). Major contribution comes from 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 2011a). For individual food products, the share of transport in total GHG emissions can be over 40% (Poore and Nemecek 2018).

Industry. Direct industrial emissions associated with food systems are generated by the fertilizer 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 contributes to food system GHG emissions with about 5% of total emissions (Poore and Nemecek 2018). Major emissions come from the use of glass, ferrous metals, and paper, therefore high shares of emissions from packaging are found for beverages (Poore and Nemecek 2018) and some fruit and vegetables (Poore and Nemecek 2018).

Waste. The waste sector contributes 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 in Mt gas yr^{-1} and share of food systems' GHG emissions to total anthropogenic GHG emissions in 1990 and 2015. Source: EDGARv5 (Crippa et al. 2019)

Sector	CO_2	CH_4	N_2O	F-gas	GHG	CO_2	CH_4	N_2O	F-gas	GHG
	Emissions (Mt gas yr^{-1})					Share of total (%)				
						1990				
1 Energy	1,900	11	0.18	-	2,200	9%	10%	25%	0%	9%
2 Industrial Processes	200	0	0	0.22	200	15%	0%	0%	0%	11%
3 Solvent / Product Use	0.40	-	-	-	0.40	0%	0%	0%	0%	0%
4 Agriculture	80	140	5.0	-	5,000	100%	100%	100%	0%	100%
6 Waste	1.9	40	0.24	-	1,300	24%	70%	100%	0%	70%
7 Other	-	-	0.11	-	28	0%	0%	22%	0%	16%
Total	2,100	200	5.0	0.22	9,000	9%	60%	80%	0%	27%
						2015				
1 Energy	2,900	12	0.20	-	3,000	9%	9%	21%	0%	9%
2 Industrial Processes	250	0	0	400	700	8%	0%	0%	40%	16%
3 Solvent / Product Use	6.0	-	-	-	6.0	4%	0%	0%	0%	3%
4 Agriculture	110	160	6.0	-	6,000	100%	100%	100%	0%	100%
6 Waste	3.0	60	0.40	-	1,700	26%	70%	100%	0%	70%
7 Other	-	-	0.15	-	40	0%	0%	22%	0%	17%
Total	3,000	230	7	400	12,000	9%	60%	80%	40%	24%

Notes: LULUCF data were not available for the FOD. Each number has been rounded to two significant digits; therefore the sum over the individual sectors does not necessarily give the value reported under 'Total'. Agricultural emissions include the emissions from the whole sector; biomass production for non-food use currently not differentiated. Methodology to other sectorial contribution to food systems' GHG emissions: (Crippa et al., in prep).

12.4.2.3 GHG intensities of food commodities

Despite large variability of GHG footprints across existing production systems, GHG footprints intensities (measured in CO_2-equivalents per kg of product) are highest for ruminant meat and high energy-intensive aquaculture (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)*. Carbon sequestration in grassland might reduce the GHG footprint in extensive production systems. Generally, beef from dairy systems has a lower footprint (18–51 kgCO_2-eq (kg meat)$^{-1}$ [1](Poore and Nemecek 2018) than beef from beef herds (40–210 kgCO_2-eq (kg meat)$^{-1}$ (Poore and Nemecek 2018) *(medium evidence, high agreement)*, due to on average more intensive production systems and feeds of higher digestibility which brings GHG footprints of dairy herds beef closer to those of meat from monogastric animals, with emissions of pork (7.4–22 kgCO_2-eq (kg meat)$^{-1}$) being higher than emissions from 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) *(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 (kg 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	110
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

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[1] Range from 10th and 90th percentile, values in kg CO2-equivalents per kg of product in retail (Poore and Nemecek 2018)

Nuts	0*	2.4
Groundnuts	0.62	2.2
Soymilk	0.58	1.5
Peas	0.25	0.75
Grains$$	0.86	3.9

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.

$$ Grains recalculated based on data provided by (Poore and Nemecek 2018)

12.4.2.4 GHG intensities of food systems

Food systems are connected to other societal systems, such as the energy system, financial system, transport system. Also, food systems are dynamic and continuously changing and adapting to existing and anticipated future conditions. Nevertheless, they can be classified on the basis of a few key descriptors such as:

- Description of food production: farm size, intensity level, farm specialization, technological level, production methods (e.g., organic, conventional, etc.) (Herrero et al. 2017)
- GHG emissions from food systems and emissions of food systems by sector, or stage of food supply chain, or differentiated by land-based emissions, energy-related emissions, and other emissions (Crippa et al., in prep);
- Length of the food chain, and role and relative power of different food chain actors, external food environments (food distribution via local markets or supermarkets; food product placement; vicinity and diversity of food options etc.) and internal food environments (cultural and religious background, food traditions; ethical standards; importance given to environmental issues, etc.)
- Importance of the agri-food sector for the overall (national) economy and jobs;
- Diets (share of food groups) and consumption preferences (convenience vs. fresh food, home vs. out eating) (Pradhan et al. 2013),
- Household expenditure on food (Chen et al. 2016; Springmann et al.).
- Level of food loss and waste (HLPE 2014; FAO 2011b; Hanson et al. 2016)
- Adequacy of the diet for healthy lives, balanced energy and nutrient intakes, avoiding of food insecurity, over-, or mal-nutrition and associated Non Communicable Diseases, or food system health outcome (Stanaway et al. 2018; GBD 2017 Diet Collaborators et al. 2019).

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 12.5). Figure 12.6 shows all countries available in the databases according to four food-system dimensions: (i) household expenditures on food; (ii) share of GHG emissions from energy use; (iii) total GHG intensities, and (iv) share of deaths attributed to one of the following risk factors: Child and maternal malnutrition, Dietary risks or High body-mass index.

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 ranges between 38% and 99%. Expenditures for food range 3.9–14 US$ cap^{-1} day^{-1}.

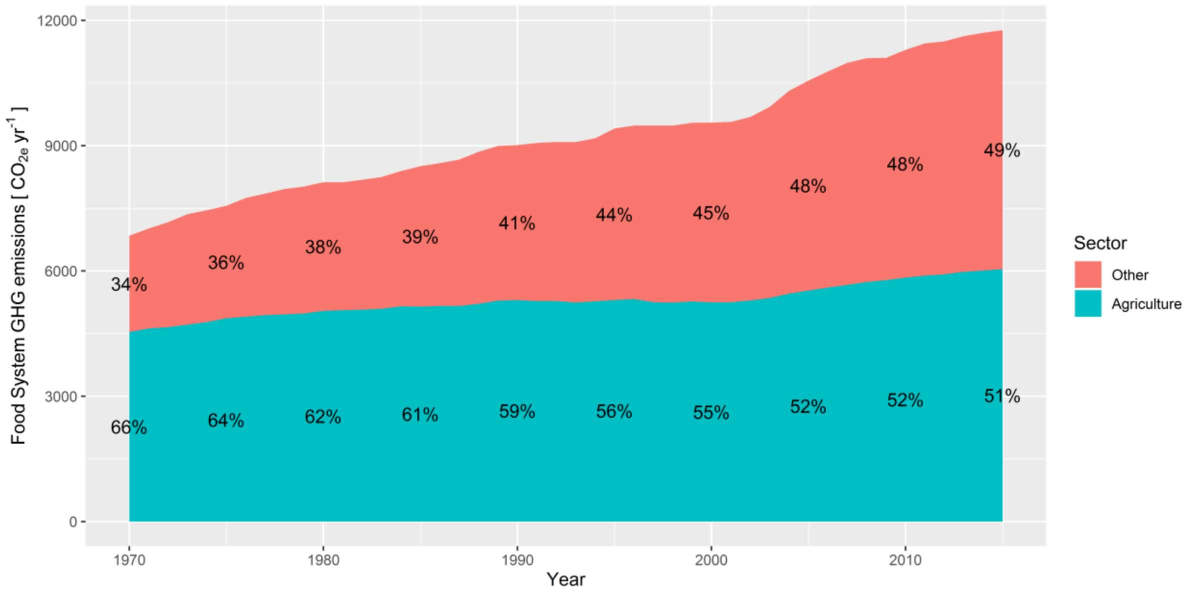


Figure 12.5 Food system GHG emissions from the agriculture sector and from other sectors (Energy, Industry, Product use, Waste, Other) (Crippa et al., in prep).

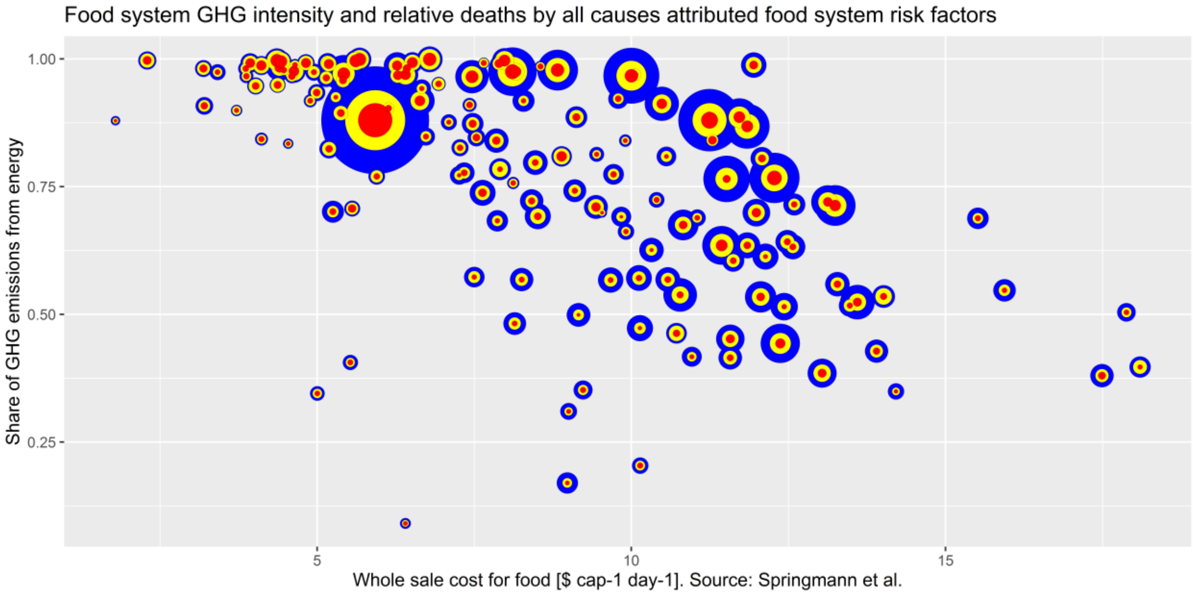


Figure 12.6 Health and GHG emissions as outcomes of national food systems. The x-axis shows the cost for food (whole sale price) per capita (Springmann et al., in review); the y-axis shows the ratio of GHG emissions from energy to GHG emissions from energy and land (Crippa et al., in prep). The size of the points shows the total food system GHG emissions in a country per capita and year (Crippa et al., in prep). The sizes of the area in the circles in red, yellow, and blue indicate 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). GHG emissions intensities are calculated on the basis of EDGAR data and represent national GHG emissions, not including emissions from LULUCF. Embodied emissions from imported goods used in the national food system are not included, and embodied emissions produced in a country but exported and consumed in another country are not excluded. The share of energy related GHG emissions can therefore be high in a country, if it hosts an industry producing goods used in more countries, such as mineral fertilizers or aluminium. (*Preliminary plot. Shares of attributed risk could also be presented as pie diagrams or assigning one colour based on the*

'dominance of risk factor' (e.g share of deaths associated to Child malnutrition > 0.6, BMI > 0.2, others). Clustering of countries into 'food system archetypes' envisaged.)

Intention to add a box with qualitative description of some 'food system archetypes', e.g. subsistence farming, modern globalized food system, typical national food systems

12.4.3 Mitigation opportunities

Significant GHG mitigation can be achieved if supply- and demand side mitigation options are implemented in combination. There are numerous food system mitigation opportunities and all food system actors can have roles in mitigation. Mitigation policies addressing also other food chain actors than food producers or consumers can significantly contribute to mitigation relating to food production and consumption.

We distinguish food system mitigation opportunities in six different categories as given in Table 12.9Table 12.9. Some of them are based on mature technologies, for which processes and causalities are understood, and their implementation is generally accepted by society. Those mitigation opportunities are 'incremental' and mainly require being implemented or scaled up. 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.

Other mitigation opportunities are based on technologies that are not yet mature and are expected to require further innovation, and production methodologies that are substantially different from existing ones, and/or are not yet widely accepted. Some of the transformative mitigation options require more thorough changes involving also a change in social norms; those are called 'disruptive'. The call for disruptive changes of current food systems has been made to underline the urgency to achieve substantial progress (EAT, Fridays for Future). Disruptions can also be 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 Beyond farm-gate food system mitigation opportunities and degree of change required

Food system mitigation options	Incremental	Transformative
Circular economy	-Anaerobic digestion$^{\$}$ -Pyrolysis$^{\$}$ -Biorefining for feed, biomaterials and energy$^{\$}$ -Landscape management to increase C sequestration^{*7} -Sewage systems$^{\$*9}$ -Circular design of packaging and materials^{*11}	-Landscape management to recover pollutants (artificial wetlands, mussel farms, landscape air filters)
Emerging Food Products & Production system	-Plant-based protein sources $^{\$}$ -Pulses$^{\$}$ -	-Bio-refineries for food$^{\$}$ -Insects$^{\$}$ -Microbial proteins$^{\$ (d)}$ -Cellular agriculture$^{\$ (d)}$ -Improved energy efficiency of lightening
Food processing industries	-Food loss and waste reduction$^{\$}$ -Food loss and waste logistics and management$^{\$*9}$ -Smart packaging$^{\$}$	-Food supplements$^{\$}$ -

	-Use of by-products -Improved energy efficiency in food production and processing[*6] -	
Storage and distribution	-Improved logistics (location, means of transport etc) in food distribution -Use of alternative fuels [*6] -Improved efficiency in refrigeration[$] -Replacing refrigerants[$] -	-Technologies improving shelf life[$] -
Options in urban environments	-Un-conditioned urban farms (school, home, rooftop gardens, …) -Ground and rooftop (conditioned) greenhouses -	-Controlled environment agriculture[$]
Diet shifts	-Change of share of livestock products, flexitarian diet[$] -Shift to organic production[$] -Shift to ‘regional and seasonal’ products[$]	-Diets with animal products based on ‘low opportunity-cost feeding’[$] -Vegetarian, pescetarian diet[$] -Vegan diet[$]

Note: $ covered in this chapter, *covered in other chapters; (d) ‘disruptive’ technology; *5 – Chapter Demand, services and social aspects of mitigation, *6 – Chapter Energy, *7 – Chapter AFOLU, *8 – Chapter Urban systems and settlements, *9 – Chapter Buildings, *10 – Chapter Transport, *11 – Chapter Industry

12.4.3.1 Circular economy approaches

Circular economy approaches can contribute to mitigation and enhance sustainability of food systems. The circular economy concept is founded on the cradle-to-cradle philosophy which considers the life cycle of any system or product in terms of its use of natural resources and environmental impacts, aiming to minimise inputs and waste (CIRAIG 2015; Withers et al. 2018). The circular economy has been illustrated as comprising two cycles, viz. the technical and the biological cycles (The Ellen MacArthur Foundation 2013; Ellen Macarthur Foundation), also known as the socioeconomic and ecological loops (Mayer et al. 2019a). The food system operates in the biological cycle, where the focus is on regeneration of the biosphere through return of nutrients (Leip et al. 2019), energy recovery and open loop recycling. In contrast, the technical cycle focusses on reuse, refurbishment and closed loop recycling to maintain value and maximise material recovery.

The conventional “take-use-dispose” linear food system mines raw materials, utilises energy in manufacture of fertilisers, removes nutrients in harvested produce that is processed into foodstuffs for consumers, with residues and waste going to landfill or being dispersed into the environment where they cause pollution of waterways, impacting biodiversity and reducing water quality. The linear flow of nutrients and organic matter from farmland to cities jeopardises future production, and is a loss of valuable resources. Landscape management can recover pollutants from environmental media – air and water – and reintroduce into agricultural production (Andersen et al. 2019).

The circular economy concept relies on a hierarchical concept that prioritizes re-use over re-cycling, and material use over energy use. To achieve this, there is the need for appropriate infrastructure (making use of existing infrastructure or establishment of new infrastructure) and logistics, as well as planning starting from product design to distribution and collection of products and residues, establishing a service industry for managing potential re-use and repair as well as a recycling industry. A shift to the circular economy requires also an increased awareness on nutrient value in ‘waste’ products such as manure (Leip et al. 2019) or sewage sludge. Modern sewage systems, for example, are designed to maximise the denitrification process (the transformation of nitrogen contained in the sewage to inert and thus harmless molecular N_2 that volatilizes into the atmosphere). The motivation is clearly the avoidance of high load of nitrogen in aquifers and harmful concentrations in drinking waters and/or eutrophication events. The consequence though is the ‘loss’ of nitrogen from the cycle, which requires that new nitrogen is “fixed” and added to the cycle (thus turned from molecular nitrogen to reactive plant-available nitrogen). Most of the new nitrogen fixation today is done with the industrial Haber-Bosch process requiring high amounts of energy and also being a direct source of N_2O emissions. Modifying sewage treatment approaches to retain N that is then applied to land would generate a significant saving in energy as well as reducing N_2O emissions, thus delivering mitigation. Alternatively, low-emitting industrial processes to fix nitrogen need to be deployed.

Around one third of food produced is lost or wasted (IPCC 2019), thus wasting the resources – land, water, energy, fertiliser, agrochemicals - utilised in production. Furthermore, decomposition of food waste in landfill releases methane. While policies and programs are now being devised to tackle the problem of food waste, some waste and loss cannot be avoided, including processing residues and inedible components. Bioenergy, particularly anaerobic digestion, is a suitable solution for managing food waste, to recover nutrients and energy, and can play a significant role in transforming the food system into a component of the circular economy.

Anaerobic digestion is an effective up-cycling process for food waste: microbial action breaks down organic wastes and manures in the absence of oxygen, to produce methane-rich combustible biogas, leaving a nutrient-rich digestate as a co-product. Biogas can be utilised for heating, or upgraded for use in electricity generation or as vehicle fuel. The digestate is a rich source of nitrogen, phosphorus and other plant nutrients, and its application to farmland returns exported nutrients. However, use of digestates as fertiliser has provided mixed results: impacts on plant growth and nutrient use efficiency are sometimes positive but have generally shown limited benefit (Möller and Müller 2012); some 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 inactivate all pathogens (Nag et al. 2019). Anaerobic digestion can be applied at a range of scales, from household to farm to large facilities, such as sewage treatment plants in large cities. Leakage of methane is a significant risk that needs to be managed, to ensure mitigation potential is achieved (Bruun et al. 2014).

Pyrolysis is an alternative technology that processes biomass residues and wastes from the food system, including food waste, manure, poultry litter and sewage sludge, into combustible gas and biochar, that can be used as a soil amendment (see Section 12.5). Pyrolysis has a particular advantage for materials that may be contaminated with pathogens, microplastics or PFAS, such as abattoir and sewage wastes, removing these risks when utilising biochar as a soil amendment to return nutrients to farmland. Conversion to biochar also aids the logistics of transport and application of materials such as sewage sludge, although challenges remain in devising cost-effective strategies for field application of biochar.

Biorefining refers to a group of process that can ‘upgrade’ biomass to produce a broad range of products including food, feed, bio-materials, and energy (Schmidt et al. 2019; Aristizábal-Marulanda and Cardona Alzate 2019). Bio-refineries have thus the potential to play a significant role in a ‘bio-economy’ society with the aim to replacing fossil fuels (Aristizábal‐Marulanda and Cardona Alzate 2019). Biorefinery plants include biogas installations, breweries and pulp and paper industries and the process is characterized by high process integration to achieve high resource use efficiency, keep down waste production and energy requirements, and to be flexible towards changing markets for raw materials and products (Schmidt et al. 2019). Here we are interested in new technologies that convert biomass that is not digestible for some organisms (e.g., algae, grass) into products that are digestible for monogastric animals or humans. For example, Lübeck and Lübeck (2019) review methods using Lactic acid bacteria (LAB) to separate green plant biomass such as grasses and clover into a protein rich fraction that can be used in pig production and other products for material or energy use. Using seaweed and algae grown in polluted waters as feedstock, and returning the nutrients back into agricultural production as feed could have a double benefit of removing nutrients from polluted waters and substituting for other feeds (Makkar et al. 2016; Makkar 2016).

12.4.3.2 Emerging food production industries

There is a large number of very diverse emerging food products and production systems. This includes some of the products discussed above as feed, such as insects, algae, mussels, products from bio-refineries. If used for humans they have stricter requirements and so not all of the production methods would be allowed. On the other hand, the use as food rather than feed allows a price premium that might turn them profitable. All of those foods 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 (animal-source) food with the aim to reduce both negative health and environmental impact.

<u>Insects.</u> Farmed edible insects have a higher feed conversion ratio with respect to other animal-sourced food and have short reproduction periods with high biomass production rates. 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 as growing substrate and industrial residues is used as main feedstock (Raheem et al. 2019b).

<u>Plant-based protein sources.</u> There is also an emerging market for meat replacements based on plant proteins, such as pulses, cereals, soya and other ingredients mainly used to imitate the taste and texture of animal-source food. Currently, the majority of plant-based protein sources (meat analogue) 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 (Gerhardt et al. 2019; Kumar et al. 2017). In particular plant based milks have seen large increases in the market share (Jönsson et al. 2019). Plant based meat analogues showed similar GHG intensities of about 0.20–0.25 kgCO_2-eq per 20 g of protein (Fresán et al. 2019).

<u>Microbial proteins.</u> A different production method to make replacements of animal products are microbial proteins that use micro-organisms to make acellular products such as proteins, for example heme, milk and egg proteins, or protein-rich animal feed (Pikaar et al. 2018). The use of fungi, algae and bacteria is an old process (beer, bread, yoghurt) and serves, among others, also for the conservation of products. 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). New technologies allow to program microorganisms such to produce a large variety of proteins.

<u>Cellular agriculture</u> produces cell tissues such as muscle cells to grow meat. Cellular agriculture is currently still in a research stage and some challenges have still to be overcome, such as the need of animal-based ingredients for fast/effective growth and the production at scale and at competitive costs (Post 2012; Rubio et al. 2019). Only few studies so far have quantified the GHG emissions of cultured meat (Tuomisto and de Mattos 2011; Mattick 2018; Mejia et al. 2019; Mattick et al. 2015; Alexander et al. 2017; Parodi et al. 2018; Post 2012).

Beside reduced GHG emissions as compared to beef, animal free foods, offer other benefits such as lower land requirements, controlled systems with reduced losses of water and nutrients, and avoiding risks from pesticide and antibiotics use or animal diseases (Sexton et al. 2019) *(medium evidence, high agreement)*, however for some future foods bioavailability and allergenic effects are not yet sufficiently studies (Garofalo et al. 2019). Plant based proteins based for example on pulses and soy have lowest GHG intensities (Smetana et al. 2015; Souza Filho et al. 2019; Parodi et al. 2018).

While microbial proteins and cultured meat lead to GHG emissions at the level of poultry meat if produced with current energy mix *(medium evidence, medium agreement)*, there is mitigation potential when using renewable energy (Pikaar et al. 2018; Mejia et al. 2019; Souza Filho et al. 2019). Microbial proteins can serve as a carbon capture technology if renewable energy is used (Pikaar et al. 2018), and technologies growing algae on methane are being developed (Ritala et al. 2017). Emissions can also be reduced if choosing substrates of low GHG intensity (Parodi et al. 2018) or growing insects on biomass residues such as food waste, if sanitary aspects are respected (Varelas 2019).

Animal-free meat products 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), but there is uncertainty whether they can 'disrupt' the food market or remain niche products. According to Kumar et al. (Kumar et al. 2017), the prospects for plant-based meat analogues it good 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.

12.4.3.3 Food processing industries

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.

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. Emissions savings through reducing food waste are achieved by both reducing wasteage of primary inputs required for food production, and reducing emissions from landfilling of waste (see Chapter 8). In developing countries in particular, most of the food waste is generated during production and processing and so this potentially represents an important opportunity for future mitigation. In developed countries more food waste is produced at the household rather than the processing stage, although the latter is no less important in terms of mitigation (Poyatos-Racionero et al. 2018; FUSIONS 2016). Where by-products and wastes are produced during food processing, these can be valorised through nutrient recovery or for energy generation or both, thereby reducing emissions from ultimate disposal and contributing to the circular economy (see Section 12.4.3.3). 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. Optimization 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 types of packaging, these need to be traded off against the life cycle emissions associated with the packaging itself. 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), 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), 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 sterilization and pasteurization (Niles et al. 2018). Packaging also plays a role here: reduced transport energy can be achieved through reducing weights of goods that are transported and improving packing densities in transport vehicles (Lindh et al. 2016; Molina-Besch et al. 2019; Wohner et al. 2019). Choice of packaging also determines refrigeration energy requirements during transport and storage.

12.4.3.4 Storage and distribution

Transport mitigation options along the supply chain include improved logistics, the use of alternative fuels and transport modes, as well as “buy local” interventions. 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 (Lemma et al. 2014), 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 and CO_2 (refrigerant R744) are among those that are being explored, to varying degrees of success (McLinden et al. 2017). In Europe it has, however, been shown that advanced refrigeration options using CO_2 only have energy savings ranging from 3% to 37.1% as compared to those using R404A which has a GWP of 3,922 (Gullo 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).

12.4.3.5 Options in urban environments

Urban farming is a concept that encompasses both un-conditioned and conditioned food production, either ground-based or linked to built structures (Goldstein et al. 2016). Un-conditioned urban farms include ground based food production such as farms in per-urban settings, in urban vacant area, school grounds, home gardens or rooftop gardens. Even though reducing the distances that food products need to be transported, un-conditioned ground-based urban farms are rarely linked or motivated by reducing GHG emissions. Often, the recreational and educational aspect is seen as more important (Artmann and Sartison 2018; Nogeire-McRae et al. 2018) or the potential to supply low-cost food for families or for charity (Coelho et al. 2018; Nogeire-McRae et al. 2018). Nevertheless, home gardens can reduce GHG emissions if replacing managed lawns and avoiding emissions from the management of organic wastes (Cleveland et al. 2017) *(limited evidence).*

Conditioned urban farming includes food production in greenhouses on ground or rooftops, as well as food production in controlled environments such as vertical farms (O’Sullivan et al. 2019; Goldstein et al. 2016). Controlled environment agriculture is mainly based on hydroponic or aquaponics cultivation. 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).

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); systems producing herbs ‘on demand’ or integrated in super-markets are emerging.

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 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). Applications of small controlled cropping systems for the production of feed in desert region in small 'farming vans' show also that there can be benefit for smallholders or families.

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 vertical farms 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) *(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 from controlled environment agriculture is independent of weather conditions and able to satisfy consumer demand of fresh and diverse produce throughout the year (O'Sullivan et al. 2019; Al-Kodmany 2018; Benke and Tomkins 2017).

Vertical farming is a very energy intensive technology (mainly for cooling) and its GHG intensity depends therefore crucially on the source of the energy. As an emerging technology with currently only a niche market share, the mitigation potential of controlled environment agriculture has not yet been assessed. Options for increasing performance and thus reducing GHG intensity of food products include reducing energy need through improved lightning 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.

Table 12.10 summarises the main characteristics of emerging food production technologies, their effect on GHG emissions, and main co-benefits and trade-offs. Those 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 were successively replaced with crop variants and cultivation practices reducing these dependencies at the cost of larger energy needs (Winiwarter et al. 2014). The effectiveness in climate mitigation lies in increasing their energy efficiency and the availability of energy from renewable sources.

Table 12.10 Emerging food production technologies and food production in urban systems

Opportunity	Main characteristics	GHG effect	Main co-benefit/trade-offs
Bio-refineries	Upgrading of plant biomass	More efficient use of biomass	
Pulses	Increasing use of pulses (incl lupines) as protein source, agronomic development of palatable varieties	No/reduced need of mineral fertilizers;	+ Beneficial for soil fertility
Mussels &Algae	Mussel farms in lagoons & close to river mouth	Substitution of crop or animal products	+ Reduction of eutrophication + Filtering out of nutrients from (polluted = nutrient

			rich) waters
Plant-based meat replacements	Plant based recipe to mimic taste & structure of e.g. minced meat for burgers	No direct (non-energy) GHG emissions from meat production	+ Animal welfare
Insects	Insect farms	Higher efficiency of transforming biomass to protein-rich food Can be fed on food waste	
Microbial proteins	Protein synthesis by micro-organisms, bacteria, fungi, yeast, and algae.	High protein conversion efficiency Can use Haber-Bosch nitrogen Energy intensive No direct GHG emissions	+ Animal welfare + Food safety + No emissions of reactive nitrogen or other pollutants - Partly uses GMO
Cellular agriculture	Tissue cell cultivation in bioreactor.	High energy need No direct GHG emissions	+ Animal welfare + Food safety
Rooftops greenhouses	Uses urban spaces to cultivate crops.	Short transport distances Cooling effect on buildings Energy requirement Land sparing	
Controlled environment agriculture	Enclosed structures of various size (modules for feeding family goats → skyscraper farms) using artificial light and controlled water and nutrient supply.	High energy intensive food production, mainly for cooling and lightning Short distance to transport, all-year & on-demand production of fresh food Building spaces can be used for renewable energy Land sparing	+ Controlled & closed-loop water and nutrient supply → minimizes losses of nutrients and water; no seasonal dependency, harvest on demand (no health 'losses')

12.4.3.6 Consumers

Diets low in meat, in particular red meat, and high in plant proteins are associated with a lower GHG intensity *(robust evidence, high agreement)*. Studies show that a shift to diets with higher share of vegetable proteins, vegetarian or vegan diets could lead to substantial reduction of GHG emissions as compared to current dietary patterns, while at the same time providing health benefits and reducing mortality from diet-related non-communicable diseases (Springmann et al. 2018a; Behrens et al. 2017; Chai et al. 2019; González-García et al. 2018; Nelson et al. 2016; Ritchie et al. 2018; Berners-Lee et al. 2012; Sabaté and Soret 2014; Weindl et al. 2017a; Springmann et al. 2018c; Costa Leite et al. 2020; Springmann et al. 2016; Tilman and Clark 2014; Clark et al. 2019) *(robust evidence, high agreement)*. Particularly in developed countries, adherence to national dietary recommendations leads to reductions of food system GHG emissions (Behrens et al. 2017), even though GHG emissions in post-farm gate stages could increase for some alternative protein sources (Chai et al. 2019). National food-based dietary guidelines currently do not include alternative diets and are only starting to include sustainability aspects (including GHG emissions) into their recommendations. However, the number of citizens choosing a flexitarian, vegetarian, vegan or other alternative diets is increasing in some countries. Several national scientific bodies have concluded that plant-based diets are healthy if some precautions are undertaken (such as vitamin B12 supplementation for vegan diets) (White and Hall 2017; Costa Leite et al. 2020).

Willett et al. (2019) propose a global healthy and sustainable diet within planetary boundaries with a daily consumption of 43 g meat per day per person for a diet of 2500 kcal per person and day, which is around a fifth of current consumption rates in western developed countries. The authors estimate a possible reduction of global food production GHG emissions from 4.7–5.4 $GtCO_2$-eq yr^{-1} in 2010 down to 2.1–3.2 $GtCO_2$-eq yr^{-1} in 2050 for vegan and vegetarian diet, with further mitigation potential for food waste reduction and increases in production efficiency. However, affordability in developing countries and the role of livestock for small scale farmers have to be taken into account (Springmann et al.; Niles et al. 2018).

Livestock play also a role in landscape management, reducing the need for herbicide use, improving soil fertility, or ensuring maintenance of landscape with high biodiversity, and there is disagreement on the net environmental impact of foods from monogastric vs. ruminant animals (Frehner et al. 2020). Feeding livestock on resources that are not used or wanted otherwise has been proposed as a mitigation option and a possibility to produce animal proteins avoiding land competition. Various studies assess the level of animal protein that could be provided from food residues and grazing on non-arable land. (Röös et al. 2017, 2016; van Hal et al. 2019; van Zanten et al. 2019; Uwizeye et al. 2019; Van Zanten et al. 2018), suggesting that 9–23 g of proteins per capita could be delivered by livestock products feeding mainly left-overs from arable land and grazing (Van Zanten et al. 2018) (*limited evidence, high agreement).*

12.4.4 Food system transitions

After the AR5, many studies on food systems that consider climate change impacts and mitigation, have used SSPs or RCPs or SPAs framework (Wiebe et al. 2015; Popp et al. 2017; Hasegawa et al. 2018; Kriewald et al. 2019; Pastor et al. 2019; van Vuuren et al. 2014; Kriegler et al. 2014). However, some studies have also developed alternative narratives to depict future food systems including diet scenarios (FAO 2018b). In general, the future food demand is considered an outcome of population dynamics and per capita consumption which depends on various factors including income, preferences, and food price sensitivities (Popp et al. 2017). 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. In this indirect approach, observed relation between income and per capita food demand is applied to estimate the future food demand under the SSPs considering the projected incomes (Riahi et al. 2011; Harrison et al. 2015). Existing studies have also considered variation on the income elasticity of food demand for regions and commodities (von Lampe et al. 2014; Hasegawa et al. 2014; Bijl et al. 2017). Increasingly, many studies are also applying direct approach on differentiating pathways of diets and food systems considering the narrative of the SSPs scenarios. These studies mainly consider dietary preferences, different level of food losses and wastes, and variation in agricultural productivity for different SSPs (Fricko et al. 2017; Lassaletta et al. 2019; Stehfest et al. 2019; Popp et al. 2017). Most studies using SSP scenarios accounted for food systems either considering the direct or the indirect approaches. Below, we briefly provide the description of pathways of diets and food systems under the SSP scenarios.

SSP1 is a scenario of sustainable development (O’Neill et al. 2014) that consists of a low population, consumption of healthy diets with limited food waste, and high agricultural productivity (Riahi et al.

2017). This scenario considers food systems with a low growth in food demand, a low meat consumption and moderate international trade (Popp et al. 2017; Lassaletta et al. 2019; Stehfest et al. 2019; Fricko et al. 2017). Diets for SSP1 also follow health guidelines in some studies (Riahi et al. 2017; Stehfest et al. 2019). SSP2 is considered as an intermediate scenario between SSP1 and SSP3 scenario (O'Neill et al. 2014), consisting of a medium population (Kc and Lutz 2014). This scenario 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). SSP3 is a scenario with a moderate economic growth and a rapidly growing population, consisting of a high inequality (O'Neill et al. 2014). This scenario considers food systems with a resource intensive consumption, a low agricultural productivity and strongly constrained international trade (Popp et al. 2017). In this scenario, demand for food and animal sourced foods grows with increase in income resulting in a high demand for animal products and a high food waste (Lassaletta et al. 2019; Stehfest et al. 2019; Fricko et al. 2017). SSP4 is a scenario with a mixed world with inequality both across and within regions with difference in economic growth (Calvin et al. 2017; O'Neill et al. 2014). This scenario also considers high inequalities in food systems with high agricultural productivity in industrial farms but low productivity for small-scale farming; elites have a high consumption but rest has a low consumption (Popp et al. 2017; Lassaletta et al. 2019). SSP5 is a scenario that focuses on technological progress driving rapid economic growth due to development of human capital (O'Neill et al. 2014; Kc and Lutz 2014). This scenario considers food systems with increase in food demand and food waste, meat-rich diets, a high level of international trade with specialized regions for certain products, and productivity agriculture with high management and inputs (Kriegler et al. 2017; Popp et al. 2017; Lassaletta et al. 2019). While operationalizing the SSPs scenarios, there are inconsistencies among the studies (Van Meijl et al. 2018), which can briefly be listed as: variation in the main driver of the total food demand (i.e., some models consider population while others income as the main driver) and variation in assumption of meat consumption and reduction of food losses and wastes across different models. Some studies also provided scenarios for specific country (e.g., China (Wang et al. 2017), United Stated of America (Antle et al. 2017)) or region (e.g., Asia (Eom et al. 2012), West Africa (Palazzo et al. 2017), three deltas across West Africa and South Asia (Kebede et al. 2018)) following the SSP narratives.

Different outcomes of the food systems have been investigated based on these SSP scenarios. Looking at food security, SSP1, SSP2, and SSP5 are considered as relatively food secure scenarios with anticipation of stresses and shocks in food availability, which would be compensated by trade in SSP1 and SSP5 (Brown et al. 2017). SSP3 and SSP4 are the scenarios with low food security, where mostly poor suffers from food insecurity while richer people and developed countries have better food security (Brown et al. 2017). This shows variation on food insecurity across the five SSPs (Hasegawa et al. 2015). Adaptation measures play a significant role in lowering the risk of food insecurity resulting from climate change (Hasegawa et al. 2014). A multiple model assessment shows negative impacts on food security of stringent climate mitigation policy across SSPs, which would be most prevalent in developing countries (e.g. sub-Saharan Africa, South Asia) (Hasegawa et al. 2018). Due to variation on demographic structure, the global average dietary requirements also vary across the SSPs resulting in different level of food waste and associated GHG emissions from the agriculture sector (Hiç et al. 2016). Some studies also look at environmental impacts (e.g. change in land use and carbon dynamics (Weindl et al. 2017a)] and required inputs for from (e.g., fertilizer (Mogollón et al. 2018) and demand (Damerau et al. 2016; Weindl et al. 2017a; Pastor et al. 2019)) food system under different SSPs.

Besides following the SSP narratives, many studies have developed alternative pathways for diets and food systems, sometime with consideration of socio-economic features of SSPs (mainly income and population). Since dietary changes towards low meat diets play a crucial role on climate change mitigation with health co-benefits (Mbow et al. 2019), it is important to explore dietary scenarios (Islam et al. 2016). Many studies considers alternative scenarios of diets together with continuation of current trends, e.g. a low animal sourced foods (Weindl et al. 2017b,a), recommended healthy diet (Bajželj et al. 2014; Springmann et al. 2018a), changes in share of macro-nutrients (i.e., carbohydrates, proteins, and fats) (Damerau et al. 2016). Beyond dietary shifts, few studies also consider other features of food systems in their scenarios, e.g. reduced food waste and closing yield gaps (Pradhan et al. 2014; Bajželj et al. 2014), nitrogen mitigation (Bodirsky et al. 2014), urban and peri-urban agriculture (Kriewald et al. 2019), different sustainability targets (Henry et al. 2018b), global vs. regionalized food systems (Kriewald et al. 2019) and agricultural carrying capacity (Sakschewski et al. 2014). Some studies have also proposed Representative Agricultural Pathways (RAPs) based on RCP-SSP-SPA framework (Wiebe et al. 2015; Antle et al. 2017). In a recent report, FAO has proposal three alternative food system scenarios: “business as usual” with continuation of past trends and policy directions, “towards sustainability” that consists of diets shifts towards healthy and balanced diets and “stratified societies” with a high consumption of animal source food and increase in food waste (FAO 2018b).

Although an increasing number of studies represents 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. The narratives consist of description of key political actors, institutional setting, food supply chain, external and personal food environment, dietary composition and health outcome, however, lack quantification of different dimension of diets and food systems. Another gap in the existing studies is the representation of future status of food security. Although studies acknowledge the four pillars of food security (availability, accessibility, utilization, and stability), most studies cover only two pillars (food availability and food accessibility) while utilization, and stability aspects hardly covered (Dijk 2014).

12.4.5 Food system policies related post-farm gate food chain actors and consumers

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 policy, food safety policies. This compartmentalization 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 (see Section 12.6.2).

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 organizations, governmental organization, civil society) are participating in the formulation of the priorities and their ranking.

12.4.5.1 Food system relevant 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., submitted) that differ in the degree they restrict the freedom of choice of food chain actors and consumers (Griffiths and West 2015; Latka et al., submitted).

Relevant economic and 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, often facing difficulties in enforcement (Kanter and Searchinger 2018) and with limited spill-over effects (Kanter et al. 2019). 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 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: Targeted policies to improve both public health and reduce GHG emissions have been shown to generate cost reductions in health care and labour force productivity exceeding the cost of the instruments (Springmann et al. 2017, 2018b, 2016)(Springmann et al.) *(limited evidence, high agreement)* and are legitimated by internalizing 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 diabetes type II and overweight or obesity, and focus on sugar intake, in particular contained in sugar-sweetened beverages which was recommended by WHO in 2017 (Park and Yu 2019; Wright et al. 2017). Even though subsidies and taxes are found to be effective in improving the dietary behaviour of consumers, depending on income group (Niebylski et al. 2015; Mozaffarian et al. 2018), measureable effects are seen only above 20% increases (Nakhimovsky et al. 2016; Cornelsen et al. 2015; Niebylski 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 people with low socio-economic status (Temme et al., submitted).

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., submitted).

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 US$ kgCO_2-eq^{-1} has been estimated at 1 GtCO_2-eq yr^{-1} (Springmann et al. 2017).

Financial instruments can effectively contribute to improve nutrition status 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) *(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 incentivizing national subsidies for farmers to remain competitive at the global market (Benton and Bailey 2019). Trade liberalization has been coined as an essential element of sustainable food systems, and trade liberalization 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). 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 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).

On the other hand, 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?

Administrative instruments.

Marketing regulations: Currently, 16 countries regulate marketing of unhealthy food to children, mainly on television and schools (Taillie et al. 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). 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 are 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., submitted), 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 mobilize private investments into emergent food production technologies can be instrumental in curbing the cost and making them competitive (Bianchi et al. 2018a).

Organizational 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, organizations 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). Procurement guidelines exist at global, national, 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, but an effect on health has not yet been detected (Cheng et al. 2018; Temme et al., submitted).

Food regulations: Novel foods based on insects, microbial proteins or cellular agriculture cannot directly be marketed but must go through an authorization 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 meat and milk analogues, regulation on the naming are required, often on demand by the livestock industry which wants protect terms like 'milk' or 'steaks' with animal-source products (Carrenõ and Dolle 2018; Pisanello and Ferraris 2018).

There are only few mandatory food system regulations, such as for example the French ban on wasting food approaching best-buy dates, and donating this food to charity organizations 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 organizations 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 2018). 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.

Informative instruments.

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., submitted). 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 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 so far not included, with the exception of red or processed meat (Temme et al., submitted). 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) or simply by lack of knowledge ‘how to use’ sustainable food alternatives (Aiking and de Boer 2018; El Bilali 2019; Temme et al., submitted). 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 sustainable life styles (McBey 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 effective (McBey et al. 2019; Temme et al., submitted). *(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. For example, a majority of EU citizens responded that a carbon footprint label should be mandatory (Van Loo et al. 2014), but carbon footprint labels have so far scarcely been used (Leach et al. 2016).

Back-of-package labels usually provide detailed neutral information (Temple 2019); front-of-package labels more often convey incentivizing signals, such as the healthy star rating implemented in Australia and New Zealand in 2014, or the Nutri-Score label developed in France in 2017 (Kanter et al. 2018), or warning signals, such as 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. 2018; Van Loo et al. 2014; Apostolidis and McLeay 2016). Carbon footprint labels are difficult to understand (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), 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 enable behavioural change in food choices. Information can be effective only 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). The food environment is the “physical, economic, political and socio-cultural context in which consumers engage in the food system to acquire, prepare and consume food” (HLPE 2017) and influence food acceptability and choices (HLPE 2017).

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). There is evidence that choice architecture (nudging) is effective in influencing purchase decisions, but so far are generally unregulated (Broers et al. 2017). Examples of green nudging include higher free offerings of healthy/sustainable products, reduced portion sizes, changing the default option, enhancing visibility, accessibility of, or exposure to, sustainable products – and reducing visibility and accessibility of un-sustainable products, or changing social norms (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). Even though supermarkets are among the main interface with the consumer (Vecchio and Cavallo 2019), data on nudging interventions to foster healthy and sustainable diets are scarce and no studies exist in the food distribution sector (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 potentially be effective (Arno and Thomas 2016; Bianchi et al. 2018b; Bucher et al. 2016) 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 globalization 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) 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., submitted). 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; Kugelberg et al., submitted). 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., submitted). National policies can be complemented – or possibly pioneered – by initiatives at the local level (Rose 2018; Aiking and de Boer 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. 2019) (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 2018; 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 engage all food system actors including civil society networks and change the food environment (Stoll-Kleemann and Schmidt 2017; Kraak et al. 2017; Cornelsen et al. 2015; iPES Food 2019; Milford et al. 2019; El Bilali 2019; Temme et al., submitted) *(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 12.11).

Possible case study: Food system strategy in Finland – reviewed and assessed by Kugelberg et al. (submitted). This could be contrasted with the Fiji approach (Latu et al. 2018) to encounter obesity.

Table 12.11 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 US$ tCO_2-eq	regressive	high	- unintended substitution effects + high spillover 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 encounters 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 spillover 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
Organizational 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 realize 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, organizational 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 spillover 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 spillover effect if mandatory	high	facilitates standardization 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 prioritization 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 Impacts, risks and opportunities from land-based mitigation

12.5.1 Overview

Chapter 7 covers mitigation in agriculture, forestry and other land use (AFOLU). The Cross-Chapter Appendix on Biomass addresses (i) the climate change mitigation effects of bioenergy and other biobased systems, considering also the associated land use and land use change; (ii) deployment of bioenergy, BECCS and other biobased options in pathways limiting warming to 1.5 or 2°C; and (iii) the biomass demands for bioenergy and other biobased applications in pathways limiting warming to 1.5 or 2°C, compared with estimates of future availability of biomass resources.

Section 12.5 covers impacts, risks and co-benefits that can be associated with land-based mitigation options (see Figure 12.7), other than those that are inherent in the food system, which are addressed in Section 12.4. Section 12.5 covers crop cultivation and residue management in agriculture, and reforestation, afforestation and management of existing forests to produce sawnwood, bioenergy and other biobased products, and/or to sequester and store carbon in vegetation and soils. Section 12.5 also covers land related impacts, risks and co-benefits associated with mitigation options that are commonly not designated land-based, but may still be associated with land occupation and consequent direct/indirect impacts. One example is hydropower that 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).

Human land use, to produce biomass and/or for other purposes, often alter ecosystem capacity to support biodiversity and a range of ecosystem services, including carbon storage in vegetation and soils. The prioritization of one land function will to a varying degree influence other functions, often (but not always) in a constraining way (IPCC 2019; IPBES 2019) *(robust evidence, high agreement)*. Thus, the deployment of land-based mitigation options will often result in opportunity costs (but sometimes gains) and possibly higher emissions elsewhere. Figure 12.7 illustrates the five "land challenges" covered by the SRCCL and the types of response options relevant to each. The figure also demonstrates the key relationships between the land surface and the climate system, including GHG fluxes and energy exchanges between the land surface and the climate system through bio-geophysical effects (albedo, evapotranspiration and heat flux, which primarily affect regional climates).

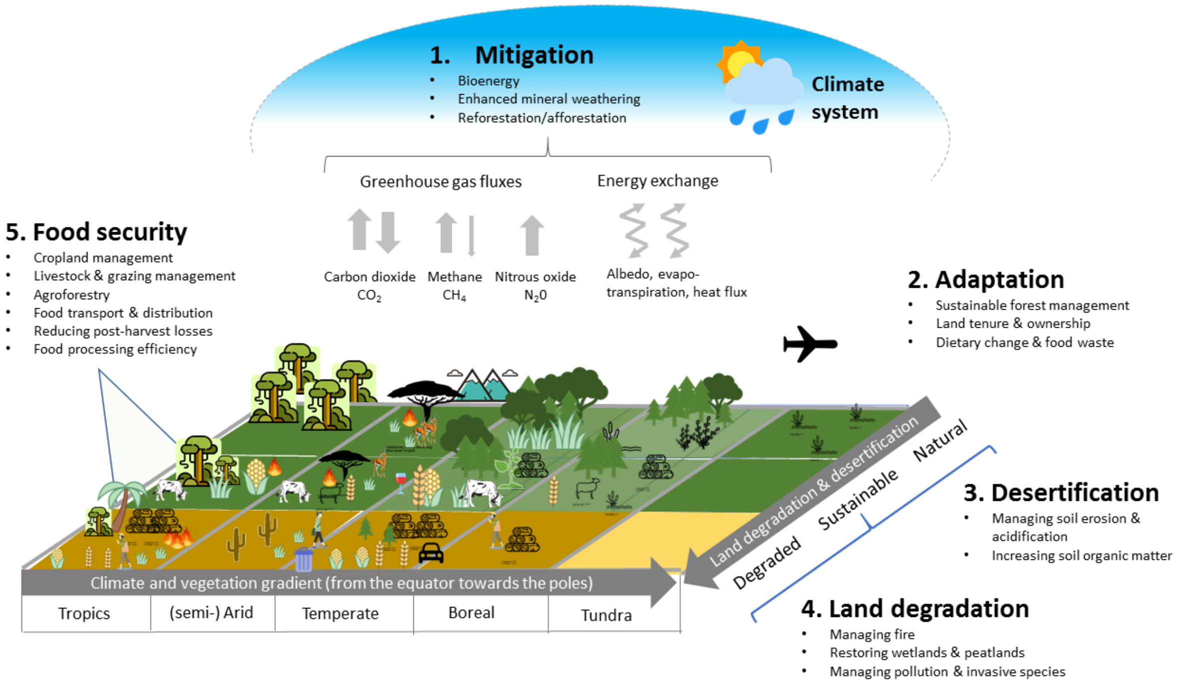


Figure 12.7 Illustration of the five "land challenges" that are covered by the SRCCL and the types of response options relevant to each. Note: the figure will be updated to also show other land uses/occupations covered in this section, such as wind, solar PV and hydropower. This figure was developed by Almut Arneth, Mark Rounsevell and Eamon Haughey.

Some land-based mitigation options are associated with the systems that provide food, sawnwood and other biomaterials, and their implementation potential depends on the size of demand for such products. Examples include the use of food waste to produce biogas, the use of sawmill residues to produce heat and power, and the extraction of crop residues to produce textiles that displace petroleum-based textiles (while ensuring sufficient residues are retained to avoid erosion and maintain/enhance soil carbon stocks). Other mitigation options can be associated with food/biomaterials systems (e.g., wood production in agroforestry systems that also store carbon and produce food products) but could also expand as dedicated systems that potentially compete for land and other resources, such as when large continuous areas are reserved for tree plantations to provide biomass for, e.g., buildings, bioenergy, biochar, and/or to sequester and store carbon in soils and trees (IPCC 2019).

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. 2019b; Hurlbert et al. 2019) *(robust evidence, high agreement)*. Results and conclusions from individual studies can therefore not easily be generalized. 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, and how governance influences conditions for land management (Lauri et al. 2019). 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; Sandström et al. 2018; Eales et al. 2018) The GHG savings achieved from producing and using forest products will in addition depend on the functioning of societal systems, since this determines the product substitution patterns (Leskinen et al. 2018). Beyond climate effects, studies have shown that the scientific literature has limited geographic coverage 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

Land occupation associated with mitigation in global/regional scenarios

The SR1.5 concludes that all assessed pathways that limit warming to 1.5°C require extensive land-based mitigation, with most including large total areas of A/R, bioenergy, and in most cases BECCS *(robust evidence, high agreement)*. Transitions in global and regional land use were found in all pathways limiting global warming to 1.5°C with no or limited overshoot, but their scale depends on the mitigation portfolio pursued. The SR1.5 states that, "considering pathways limiting warming to 1.5ºC with no or limited overshoot, the full set of scenarios shows conversion of 0.5–11 Mkm^2 of pasture into 0–6 Mkm^2 for energy crops, a 2 Mkm^2 reduction to 9.5 Mkm^2 increase in forest, and a 4 Mkm^2 decrease to a 2.5 Mkm^2 increase in non-pasture agricultural land for food and feed crops by 2050 relative to 2010" (Rogelj et al., 2018, p. 145). 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 (some 21 Mkm^2 of savannahs and shrublands are also used for grazing) (IPCC 2019). 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.

The SRCCL reports that implementation of mitigation options that limit warming to 1.5°C or 2°C would require conversion of land for A/R and bioenergy crops, which could lead to short-term carbon losses *(high confidence)*. The change of global forest area in mitigation pathways ranges from about –0.2 to +7.2 Mkm^2 between 2010 and 2100 (median values across a range of models and scenarios: RCP4.5, RCP2.6, RCP1.9), and the land demand for bioenergy crops ranges from about 3.2 to 6.6 Mkm^2 in 2100 (Shukla et al. 2019). Depending on the desired climate outcome, the portfolio of 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 mitigation options can facilitate other options; for example, dietary change and waste reduction may reduce land demand by 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), expanding the potential for other land based options (Smith et al. 2019b). Stronger mitigation action in the near term, including early CDR, 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).

Land occupation associated with other mitigation options is rarely quantified in global scenarios. Among studies available, (Luderer et al. 2019) modeled land occupation and land transformation associated with a range of alternative power system decarbonization pathways in the context of a global 2°C climate stabilization effort. On a per-MWh basis, electricity combined with BECCS 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 (Figure 12.8) (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 character of land occupation differs. For example, the use of agriculture and forestry residues as bioenergy feedstock represents an additional use of already occupied land rather than additional land occupation. As discussed below, agriculture, forestry and other activities can also co-exist within the boundaries of wind power and solar power installations (See Section 12.5.2.2).

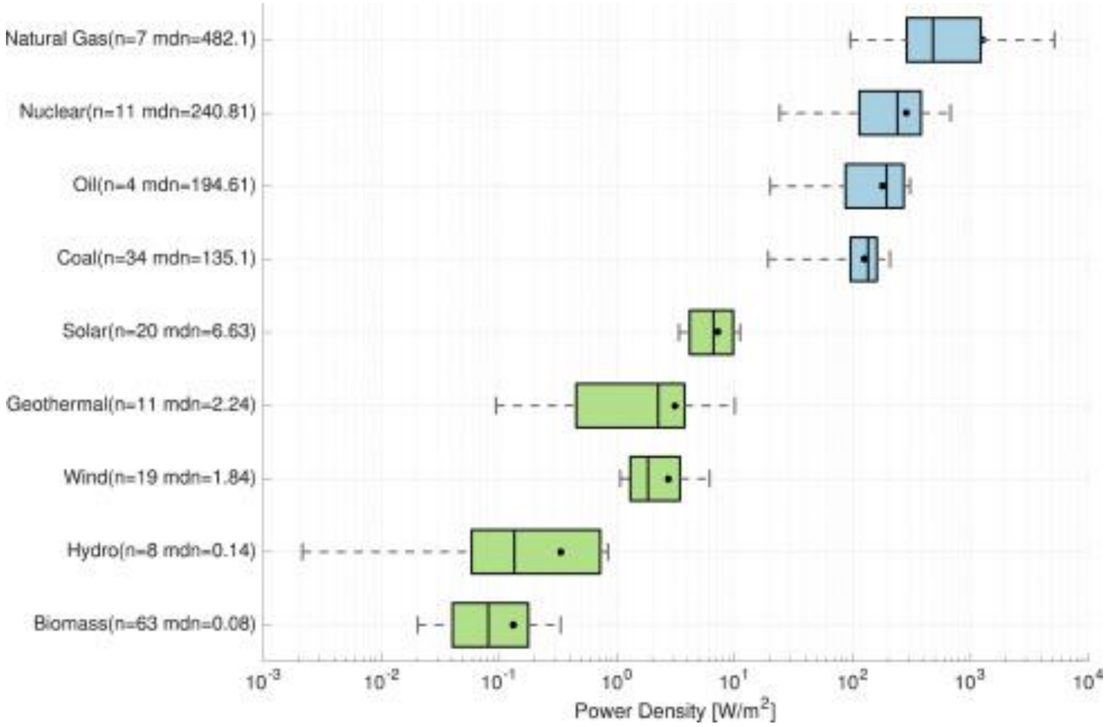


Figure 12.8 Box plots of power densities for different energy options visualized on a log scale. The annotations n and mdn give the number of values found for each energy type, and the median power density respectively. Outliers are those values that are further away than 0.5 and 1.5 times the 1st and 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. Note that the figure does not capture influence of load factors and intermittency aspects. Source: (van Zalk and Behrens 2018)

<u>Impacts of land occupation.</u> Many different deployment strategies could be implemented to achieve the scale of land-based mitigation that occurs in pathways limiting global warming to 1.5°C or 2°C. Global modeling studies provide information on how different mitigation options contribute to emissions reduction at global and regional levels. They provide information about the area occupation and land use carbon flows of different land-based mitigation options, but they rarely consider land occupation associated with other energy options than bioenergy.

Recently, scenarios from IAMs have been combined with LCA to investigate environmental impacts associated with alternative mitigation choices. The approach to combine IAMs and LCA enables quantification of a wider variety of environmental effects and how these depend on context conditions. (Luderer et al. 2019) found that the scale and character of co-benefits and adverse side effects depend strongly on technology choice. Specifically for bioenergy and BECCS, policies (land sector carbon taxes) and energy crop production practices had a very strong impact on environmental impacts. Overall, variations in impacts due to uncertainty in bioenergy demands across models as well as policy and management practices exceeded variations across technology scenarios (Arroyo-Currás et al. 2015; Luderer et al. 2019).

The character of land occupation – and consequently the associated impacts – varies considerably among mitigation options and also for the same option depending on geographic location, scale, system design and deployment strategy (Olsson et al. 2019) *(robust evidence, high agreement).* For example, land occupation associated with different mitigation options can be large uniform areas (e.g., large solar parks, hydropower dams, or monoculture plantations of exotic tree species), or more distributed occupation, such as when wind turbines and patches of biomass plantations are integrated with other land uses in heterogeneous landscapes (Jager and Kreig 2018; Englund et al. 2020; Correa et al. 2019; Cacho et al. 2018). The stylized representation of land occupation associated with different mitigation options in global models, does not support comprehensive exploration of diverse and geographically distinct development pathways for land-based mitigation, shaped by local context conditions.

Complementary to global models, studies with smaller geographical scope apply more refined representations of possible deployment routes and land occupations associated with different mitigation options. They can provide complementary information needed to advance the understanding of how deployment of land-based mitigation may become shaped by context conditions that will vary geographically and over time. Relevant design and implementation require considering people's needs, biodiversity values, and other sustainable development dimensions. Implementation will therefore differ depending on context conditions and prioritization among societal objectives. Thus, it is expected that the region/context specific solutions, which combine to provide the large-scale mitigation, will be associated with contrasting regional land occupation patterns – and hence impacts, both good and bad.

As further discussed in Section 12.5.2 and Section 12.5.3, mitigation options can present challenges related to trade-offs associated with the land occupation, such as if bioenergy crops, forestation projects, solar power parks 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, such as when perennial grasses and woody plants are introduced in existing agriculture landscapes to mitigate erosion, soil carbon losses and other impacts of current land use.

12.5.2 Land, water and ecosystems

> *This sub-section cover risks, impacts and co-benefits related to the status of land, water and ecosystems. Methodological approaches to assess climate effects are covered in the Biomass Appendix.*

12.5.2.1 Risks and impacts, and their mitigation

- Some mitigation options remain to be covered
- The text on water and ecosystem impacts and risks is incomplete

Land. As noted above, mitigation options that are based on the use of land/biomass (A/R, bioenergy, biochar and other biobased products) may cause different – positive and negative – impacts depending on the character of the land use/biomass supply system, previous land/biomass use, the biomass conversion process, and how the biobased products are used. The impacts of the same mitigation option can therefore vary drastically.

There is potential for land degradation through nutrient decline, soil erosion and decline in SOM, 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 cropping, or if too much of the crop or forestry residue is extracted from the land.

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 SOM, and by replacing nutrients removed, such as by applying ash from bioenergy combustion plants (Harris et al. 2015).

For re-/afforestation, the risk to land will primarily be associated with situations where the establishment of tree cover displaces the previous land use to new locations, especially if this indirectly causes deforestation. If the forests that become established are managed for production of wood and non-wood forest products, they will on the other hand reduce deforestation pressure that is caused by demand for such products. In this regard, re-/afforestation for the sole purpose of sequestering and storing carbon may be associated with a higher risk of causing indirect deforestation (ceteris paribus).

The land requirements and also the impacts (including visual impacts) of on-shore wind power depend on the type and size of installations. A small share 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. Solar thermal and PV installations can hinder other land uses. However, these options use less land per unit of energy output than most other non-fossil options.

Establishment of large-scale solar parks 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 per unit of energy output is relatively small (Figure 12.8). However, nuclear accidents can lead to land contamination due to release of radioactive material. The 1986 Chernobyl accident in the Ukraine resulted in radioactive contamination being spread across Europe. About 125,000 km^2 of land in Belarus, Ukraine and Russia was contaminated. More than one-third of this land was used for agriculture and agricultural products, livestock, and soil were contaminated. About 350,000 people were resettled away from these areas (Sovacool 2008). Land areas in several European countries were also contaminated (Strebl et al. 1999; IAEA 2006) . The 2011 Fukushima Nuclear Power Plant accident resulted in the contamination of a large (mainly forested) area in eastern Japan (Buesseler et al. 2017). Studies indicate that forest harvest, especially clearcutting, may cause soil loss and sediment export that in turn cause ^{137}Cs contamination in downstream areas, including floodplains, reservoirs, and irrigated cropland (Evrard et al. 2015; Nishikiori and Suzuki 2017).

Hydropower can offset or exacerbate impacts of changing climate, water use and land use, thus affecting downstream communities in positive or negative ways (Hecht et al. 2019). Hydropower reservoirs submerge areas and may entail the relocation of communities living within or near the reservoir or construction sites, which can have both socio-economic and environmental consequences including those associated with establishment of new agricultural land (Zarfl et al. 2019; Latrubesse et al. 2017). Dam construction also stimulates migration into the affected region, and large influxes of people can lead to deforestation and other negative impacts.

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 vegetation in the flooded area. Quantifications indicate that the magnitude of GHG emissions and C sequestration losses caused by inundation can be significant. 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 contribute a significant part of the cumulative GHG emissions of hydroelectric power plants (Ocko and Hamburg 2019).

Water. As for impacts on land, the water-related impacts of land-based options depend on the type of mitigation option, where and how it is deployed, and how the land was used previously. Substantial volumes of water may be used for biomass processing to produce biofuels and other biobased products. Most water is returned to rivers and other water bodies and is therefore available for further use. Negative impacts can occur due to chemical and thermal pollution loading the aquatic systems.

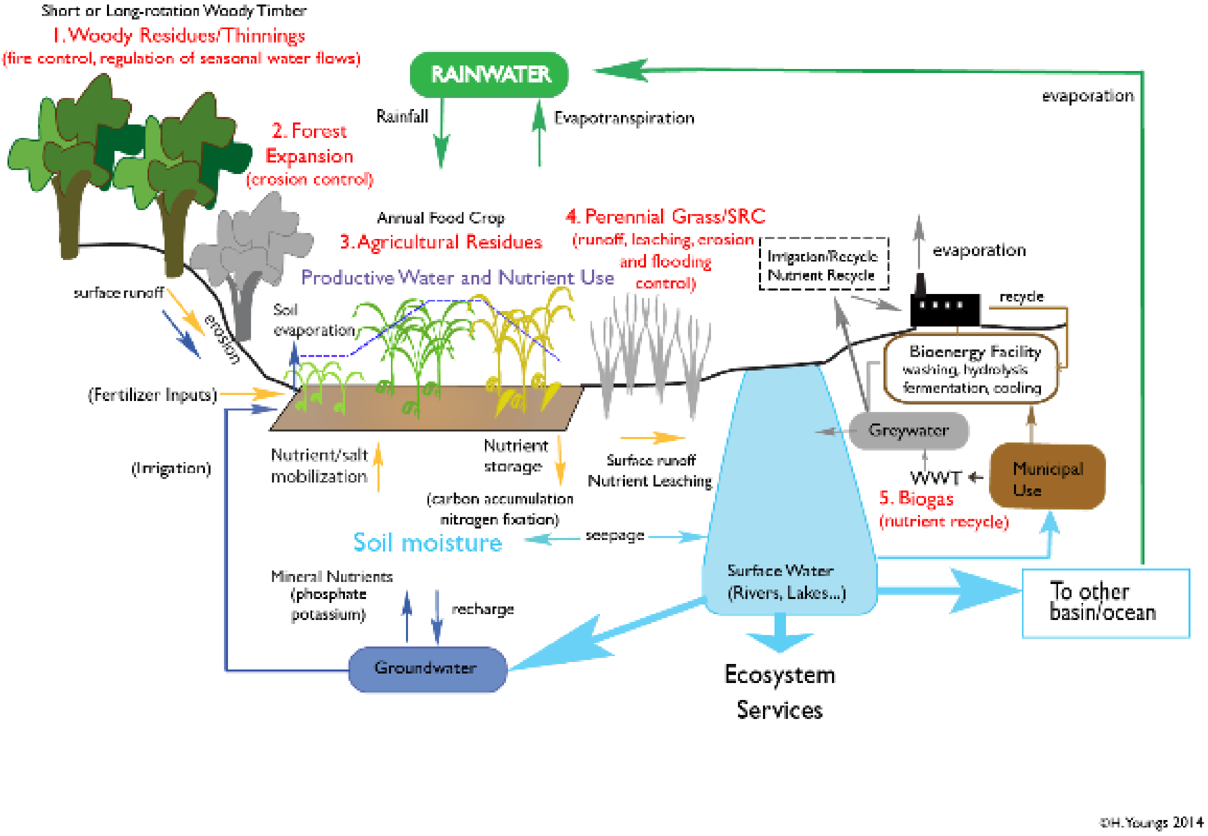
Biomass production can require much more water than the processing to produce biobased products. Much of this water is evapotranspired back to the atmosphere and is therefore not available until it returns via precipitation. Rainfed biomass production does not require water extraction from groundwater, lakes, and rivers, but it can still reduce downstream water availability by redirecting precipitation from runoff and groundwater recharge to crop evapotranspiration. Also A/R can increase evapotranspiration and thus reduce groundwater and downstream water availability (Farley et al. 2005; Lu et al. 2018; Zhang et al. 2016, 2017).

Adverse effects can be mitigated and synergies achieved when plantings are cited carefully, with consideration of hydrological impacts (Davis et al. 2013). While increases in evapotranspiration can have adverse consequences for agriculture, natural ecosystems and settlements, it can be beneficial where historical clearing has caused dryland salinity, soil salinization and stream salinity (Farrington and Salama, 1996; Marcar, 2016). Some other examples of beneficial effects have already been mentioned, e.g., 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). (Garg et al. 2011) found positive effects of land-use change to cultivate Jatropha on wastelands previously used for grazing, which could continue in the Jatropha plantations: non-productive soil evaporation was reduced as a larger share of the rainfall was channeled to productive plant transpiration and groundwater recharge, and at the same time a more stable (less erosive) runoff resulted in less soil erosion and improved downstream water conditions.

Ecosystems. The impact of land-based mitigation options on ecosystems varies markedly between the options, and depends also on their method and site of deployment. Land-based mitigation options that enhance biomass carbon 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). Expansion of energy crops can pose risks to natural ecosystems through land use change and introduction of invasive species (Liu et al. 2014). Nevertheless, 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). 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). Tradeoffs between different ecosystem services, and between societal objectives, 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).*

12.5.2.2 Co-benefits and their promotion

Perennial grasses and woody plants can be integrated 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 12.9 Overview of opportunities related to selected land based climate change mitigation options. Source: (Berndes et al. 2015)), hence reducing impacts from intensive agriculture on land, water and ecosystems. 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).



Sustainable land management can simultaneously contribute to climate change mitigation, climate change adaptation and reduced risk of land degradation (IPCC 2019) (*robust evidence, high agreement*). For example, proven agronomic measures such as cover crops, intercropping, stubble retention and switching from annual to perennial crops or pastures can prevent and reduce soil erosion and nutrient leakage, as well as increasing soil carbon stocks (Culman et al. 2013; Poeplau and Don 2015; Conant et al. 2017; Kaye and Quemada 2017; Sainju et al. 2017; Henry et al. 2018a). More novel approaches such as applying biochar to soil sequesters carbon (Singh et al. 2012; Wang et al. 2016a; Han Weng et al. 2017) and can improve soil conditions. 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 reduce nutrient leaching (Singh et al. 2010; Haider et al. 2017) and enhance crop yields particularly in infertile acidic soils

(Jeffery et al. 2017), and contribute to climate change adaptation through increased water-holding capacity (Quin et al. 2014; Omondi et al. 2016) (See Chapter 7 for review of biochar contribution to climate change mitigation). Novel perennial grain crops, such as perennial wheat, are expected to reduce soil erosion, increase nitrogen retention, have higher water use efficiency and enhance carbon sequestration, compared with annual crops (Crews et al. 2018).

Site-specific technological solutions that help adapt to climate change at the same time as combating desertification include: adaptive restoration to improve techniques for optimising rain use efficiency in plantations; adjusting land use by using natural vegetation and exploring native plant species' drought resilience; agroforestry; ecosystem-based adaptation; incorporating conservation tillage; and using modern information and communication technologies for monitoring and early warning systems.

Afforestation programs for the creation of windbreaks can reduce sand storms, avert desertification, and increase carbon sinks. Measures that sequester soil carbon also contribute to climate change mitigation and biodiversity conservation. Natural vegetation restoration and establishing plantations in degraded land enable organic carbon to accumulate in the topsoil and subsoil and has potential to deliver significant co-benefits for biodiversity, land resource condition and livelihoods.

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

Solar thermal and solar PV systems can be integrated into buildings and other structures. Deserts and other land areas with few alternative uses can be suitable for solar power installations, although remote locations may pose challenges for power distribution. 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. Approaches with PV systems are being researched that may achieve significant power generation without potentially 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),

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 bioenergy and other 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) 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.

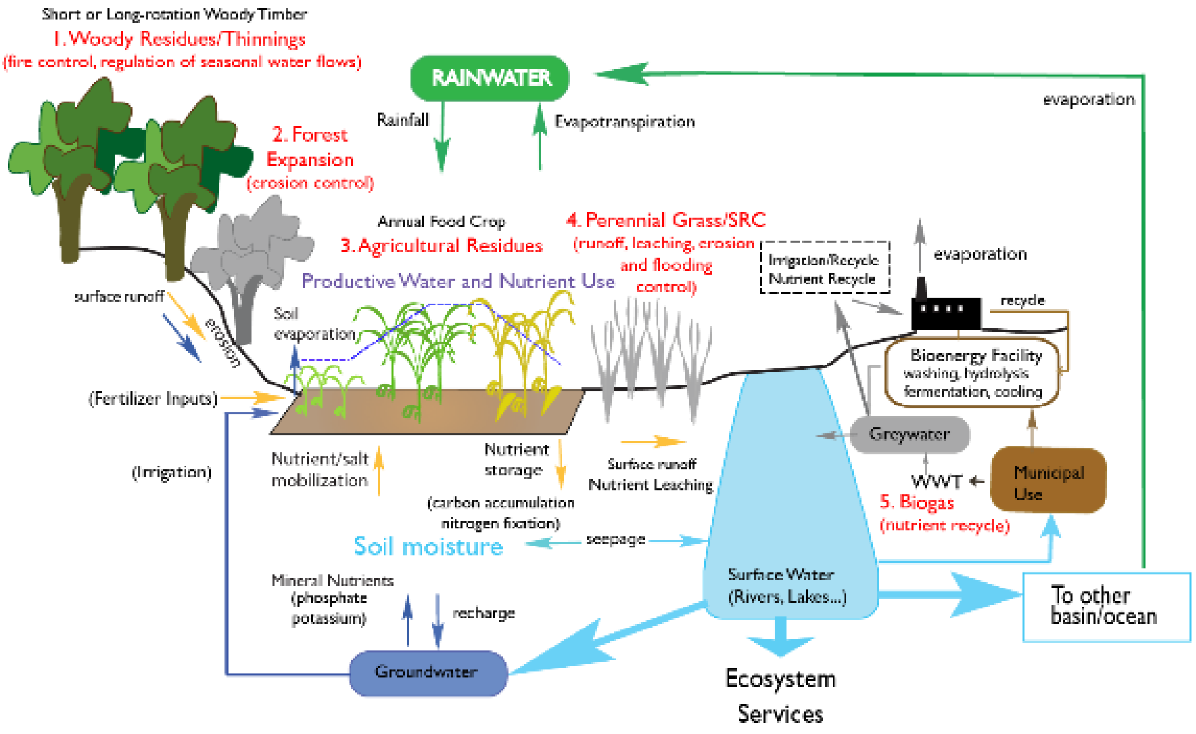


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Figure 12.9 Overview of opportunities related to selected land based climate change mitigation options. Source: (Berndes et al. 2015)

12.5.3 Food security

12.5.3.1 Risks and impacts

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.

The pressure on agricultural land – and therefore food security risks – 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.

Re-/afforestation 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. However, there are large tracts of less-productive land, degraded land, marginal land and abandoned land that 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 A/R). 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 farmers 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. 2019b).

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, or maintenance of the productivity of the land resource base:

- Improved forest management, reduced deforestation and forest degradation are mitigation measures applied on land that is not used for intensive food production
- Sustainable land management practices such as cover crops, grazing management and agroforestry build soil organic matter, and thereby sequester carbon and enhance resilience of agro-ecosystems, thus contributing to long term food security while addressing land degradation as well as mitigating and adapting to 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 carbon plantings, energy crops (such as perennial grasses) and agroforestry can improve 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 and biobased 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 utilized for food production.

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

- Enhanced weathering, that is, adding ground silicate minerals to soil to take up atmospheric CO_2 through chemical weathering, can enhance crop yields (Haque et al. 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 was increased under elevated solar panels. Agriculture can coexist in beneficial ways with wind power.

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).

Table 12.12 summarises how different land-based mitigation options are associated with risks, impacts and opportunities related to the status of land, water and ecosystems *(to be completed)*.

1 **Table 12.12 Impacts, risks and co-benefits associated with land-based mitigation options**

Mitigation option	Impacts and risks	Opportunities
Non-biobased options that may displace food production		
Solar power parks	Land use competition; Loss of soil carbon; heat island effect (scale dependent)	Integration with agriculture; Target areas unsuitable for agriculture
Hydro power (dams)	Land use competition, CH_4 emissions	Water storage and regulation of water flows
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)	Sited to minimise impact on food production
Solar panels	Land use competition	Placed on roofs and other out-of-the-way places; Approaches to integration with benefits for food production is being explored
Biobased options that displace food production		
Re-/afforestation	Land use competition; reduced water availability; loss of biodiversity	Strategic siting to minimise adverse impacts on hydrology, land use, biodiversity
Biomass plantations	Land use competition; reduced water availability; reduced soil fertility; loss of biodiversity	Strategic siting to minimise adverse impacts on hydrology, land use, biodiversity, provide benefits for water quality
Biobased options that can (to a varying degree) be combined with food production		
Agro-forestry		
Improved cropland management (increasing C stock in vegetation and soil)		
Crop rotations with grass crops		Improved soil conditions and increases in soil carbon; reduced need for pesticides
Improved grazing land management (increasing C stock in vegetation and soil		
Biochar addition to soil		
Harvest residue extraction and use for bioenergy and other biobased 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)	
Forest management	
Reduced deforestation and degradation	Prevents expansion of land used for food
Forest restoration (on forest land)	
A/R on degraded non-forested land (e.g. abandoned agricultural land)	
Fire management in forest land	Biodiversity impacts
Restoration & reduced conversion of coastal wetlands	Land use competition for urbanisation, infrastructure
Restoration & reduced conversion of peatlands	

12.6 Other cross-sectoral implications of mitigation

Previous Sections have presented a synthesis of the costs and benefits of mitigation action across the sectors, have discussed technologies for carbon dioxide removal, and have presented considerations related to land use and food – many of which are linked to the different sectors presented in Chapters 5 to 11.

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

12.6.1 Cross sectoral perspectives on mitigation action

Cross sectoral perspectives on mitigation action covered here include those related to the co-benefits and adverse side-effects of mitigation action, mitigation actions that contribute to mitigation in more than one sector and general purpose technologies that have relevance to multiple sectors.

12.6.1.1 The link between co-benefits and adverse side effects of mitigation actions and the SDGs

A body of literature has been developed which addresses the *co-benefits* of climate mitigation action, being the additional benefits to society and the environment that are realised in parallel with emissions reductions. *Adverse side effects* of mitigation are also well documented, highlighting where policy and decision makers are required to make trade-offs between mitigation benefits and other impacts. The identification and assessment of co-benefits has been argued to serve a number of functions 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)*. 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)*. Co-benefits and adverse side-effects in individual sectors and associated with individual mitigation actions are discussed in the individual sector chapters, 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). Various approaches to identifying and organising co-impacts in specific contexts have been proposed towards providing more comparable and standardised analyses. However, 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).

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 co-impacts of mitigation action and global government policies is being clearly considered is in the achievement of the SDGs (Obergassel et al. 2017; Markkanen and Anger-Kraavi 2019; Smith et al. 2019a). Figure 12.10 below demonstrates the links between sectors which give rise to emissions, the mitigation actions that can find application in the sector, co-benefits and adverse side effects of mitigation actions and the SDGs (based on concept used in Smith et al. (2019a)). Such a framing of co-impacts 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.A.

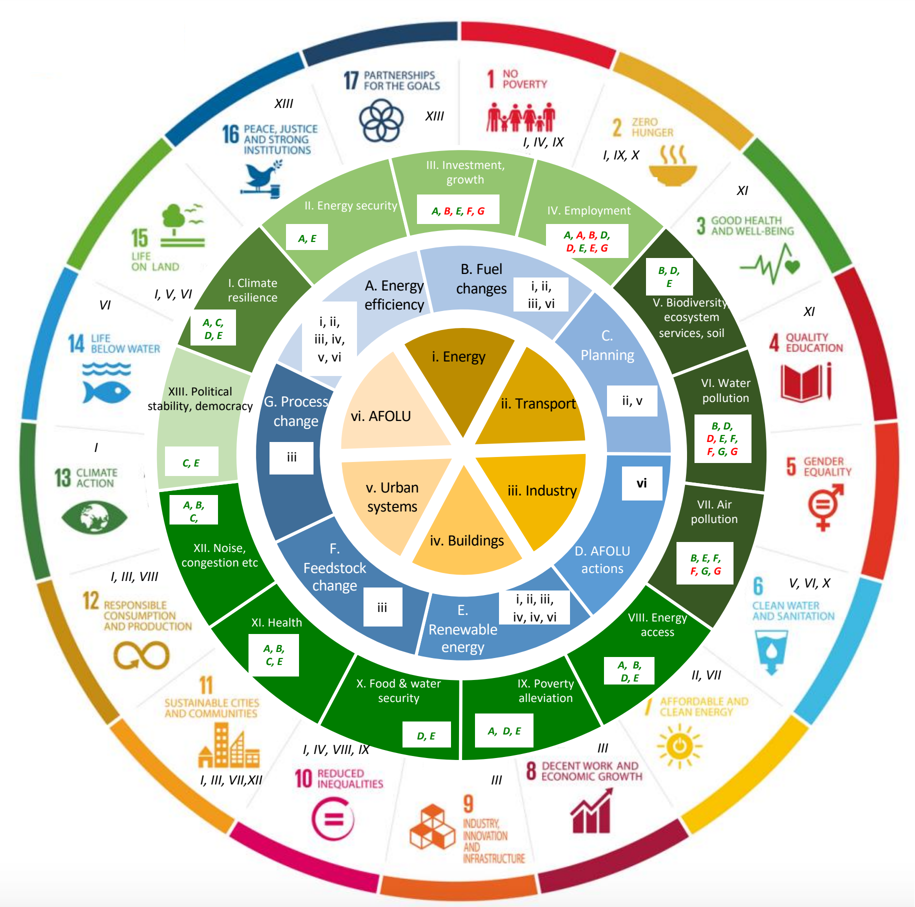


Figure 12.10 Co-benefits and adverse side effects of mitigation actions with links to the SDGs. The inner circle represents the sectors in which mitigation occurs (i to iv). The second circle shows different generic types of mitigation actions (A to G), with the small roman numerals showing which sectors 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 sector;
- implications of mitigation measures for interaction 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 (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 (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) has potential application in a number of industrial processes (cement, iron and steel, petroleum refining and pulp and paper) (Leeson et al. 2017) and the fossil fuel electricity sector (see Chapter 6). When coupled with energy recovery from biomass (BECCS), CCS can provide a carbon sink (see Section 12.3).

A range of examples of where mitigation measures result in cross-sectoral interactions 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). 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 (see Cross-Chapter Appendix on Biomass). 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 Cross-Chapter Appendix on Biomass). 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. At the same time, 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 have been presented in Section 12.2.

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 is also relevant elsewhere. Constraints have been identified in the supply of indium, tellurium, silver, lithium, nickel and platinum that are required for implementation of different 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 benefits of emerging general purpose technologies

Various General Purpose Technologies (GPTs) have been identified that have a role to play in mitigation of GHG emissions (de Coninck et al. 2018). Table 12.13 identifies the GPTs, sectors in which they might find application. It is highlighted that assessment of the environmental, social and economic implications of such technologies is challenging, and furthermore that rebound effects could occur (de Coninck et al. 2018). One important such emerging technologies is hydrogen, which has a number of uses with associated synergies and trade-offs for mitigation of GHGs in key sectors including energy, industry, transport, and buildings (see Box 12.1).

Table 12.13 Cross-sectoral applications of General Purpose Technologies *(to be filled further for SOD)*

GPT	Sector applicability	Examples of specific applications

Additive manufacturing (3D printing)	Transport	Aircraft component manufacture to achieve more lightweight, cost-effective designs results in improved fuel consumption and lower primary resource inputs. Estimated life-cycle for the US aircraft fleet could achieve primary energy savings of 70–174 million GJ yr^{-1} in 2050, with cumulative savings of 1.2–2.8 billion GJ. Associated cumulative emission reduction potentials of CO_2-eq were estimated at 92.8–217.4 million metric tons (Huang et al. 2016)
Artificial Intelligence (AI)	Agriculture Buildings	Applications in agriculture include irrigation management which can reduce power requirements for pumping and optimisation of energy for produce storage (Bannerjee et al. 2018)
Biotechnology	Agriculture Transport	
Hydrogen	Energy Industry Transport	Hydrogen, which can be produced from a number of different fossil and renewable resources, finds application in transport, industry and distributed generation (Hanley et al. 2018; Mayer et al. 2019b).
ICT	Buildings Energy Transport Urban systems	ICT has been demonstrated to have potential to contribute to increased household energy efficiency. One estimate suggests ICT-based interventions in household energy use could contribute between 0.23% and 3.3% of the EU CO_2-eq reduction target from the energy sector, corresponding to 4.5–64.7 $MtCO_2$-eq abated per year (Bastida et al. 2019).
Internet of Things	Energy Transport Urban systems	
Nanotechnology	Energy Transport	Nanotechnology has played a significant role in advancement of all the different types of renewable energy options (Hussein 2015). Carbon fibres were originally developed for structural applications. They have, however, demonstrated potential as high capacity negative

		electrodes in Lithium ion batteries where they can offer both a structural and electrochemical function (Fredi et al. 2018).
Robots	Industry	

Box 12.1 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 AR5 was published. A recent report (IEA 2019a) provides and overview. Hydrogen already plays an important role in the chemical sector (ammonia and methanol production) and in the fuel sector (oil refineries and biofuel production). The IEA observes a potential for further expansion of the use of hydrogen and hydrogen-derived fuels in industry. In addition, the IEA already sees opportunities in 2030 for buildings, road freight and passenger vehicles. In the longer term, they also see a high potential application in iron and steel production, aviation and maritime transport, and for electricity storage.

Several industry roadmaps have been published that sketch a possible role for hydrogen until 2050. The most well-known and ambitious one is the roadmap by the Hydrogen Council, 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); the European Commission (EC 2018), and 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).

Production costs of green hydrogen are expected to come down from the current levels of above 100 US$ per MWh. Price expectations are: 40–60 € MWh-1 for both green and blue hydrogen production in the EU by 2050 (Navigant 2019) with already lower production costs in North Africa; 42–87 US$ MWh-1 for green hydrogen in 2030 and 24–30 US$ MWh-1 in 2050 (BloombergNEF 2019); 75 € MWh-1 in 2030 (Glenk and Reichelstein 2019). Such prices will make hydrogen competitive for industrial feedstock applications, and probably for several transportation modes in combination with fuel cells, but without further incentives, not for stationary applications in the coming decades: wholesale natural gas prices are expected to range from 12–39 US$ MWh-1 across regions and scenarios, according to the World Energy Outlook (IEA 2019b); coal prices typically are a factor 2 lower than that (all fossil fuel prices refer to unabated technology). 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 a decent 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 1.6% in 2050 and 5.4% in 2100 (Figure Box 12.1) [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 rarely reached in the scenarios. Hydrogen is predominantly used in the industry and transportation sectors. Hydrogen is produced mostly by electrolysis and by biomass energy conversion with CCS (Figure Box 12.1). 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 in virtually all sectors. However, there is less agreement on timing and volumes, and even on the production methods of hydrogen.

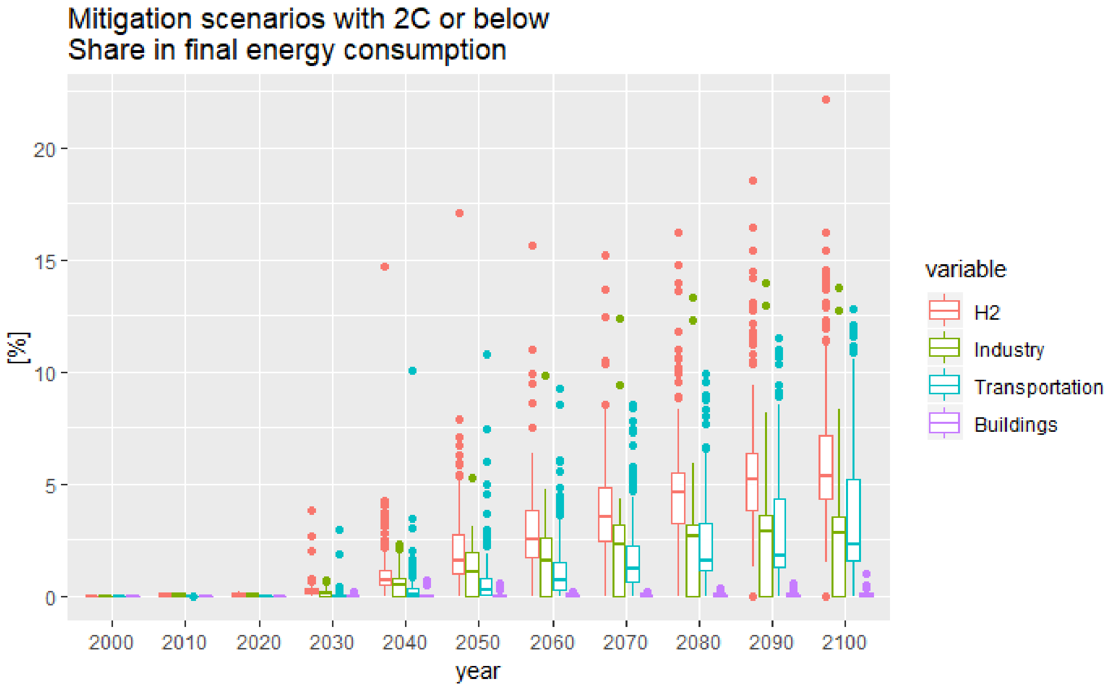


Figure Box 12.1 Fraction of hydrogen (H_2, red) in total final energy consumption, and those for each sector. The upper and lower whiskers extend from the hinges no further than 1.5 times the interquartile range from the hinges; other results are presented as outliers and plotted as points.

12.6.2 Sectoral policy interactions (synergies and trade-offs)

Synergies and trade-offs resulting from mitigation policies are not clearly discernible from either the sector-specific studies nor the global and regional top-down studies literature. They 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 double counting (Ürge-Vorsatz et al. 2014) *(robust evidence, high agreement).*

Literature comparing top-down (IAM) and bottom-up (sectoral) approaches to climate-economic modelling (assessed in IPCC AR4, IPCC AR5, IPCC SR1.5) often includes comparisons on the response options included in both approaches (and why they differ). There is less literature specifically on policy/governance assumptions in modelling (Pauliuk et al. 2017; Geels et al. 2016; Li and Strachan 2019).

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, (Wang et al. 2016b) find that a pure carbon tax without revenue recycling in developed economies tends to be regressive, e.g. lower income households being more affected; and in terms of sectoral distributional implications studies (Wang et al. 2016b; Åhman et al. 2017; Rausch and Karplus 2014) find negative competitiveness impacts for the energy intensity industries *(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 spillovers (Galik et al. 2019). To maximize synergies and deal with trade-offs in such a cross-sectoral context, an evidence-based/informed policy approach that takes into account unanticipated outcomes and indirect consequences would be needed (Klausbruckner et al. 2016) *(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 2C and 1.5C.

12.6.3 International trade spillover effects and competitiveness

Cross-sectoral international spillovers 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 spillovers; 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).*

12.6.3.1 Carbon leakage - empirical evidence

Carbon leakage occurs when mitigation measures implemented in one country/sector lead to the rise of emissions in other countries/sectors. Under the Kyoto protocol, the problem of leakage followed from uneven distribution of commitments between Annex I and non-Annex-I countries. The Paris Agreement eliminated this but instead its very bottom-up structure gave rise to climate policies and ambitions that are very uneven both country- and sector- wise, which may provoke carbon leakage. Three essential channels for carbon leakage are: 1) stringent climate policies may increase local costs of producers which undermine their competitiveness compared to those in countries with less stringent mitigation policies; 2) the loss of competitiveness as a result of mitigation measures is so strong that not just production but investments move to jurisdictions with no or weaker climate policy; 3) mitigation policies put a downward pressure on fossil fuels prices that leads to larger fossil fuel consumption in countries with no or weaker climate policies. Carbon leakage channels 1) and 2) will be considered in this sub-section, while the channel 3) will be described in Section 12.3.3.2.

A large set of literature pursued the objective of testing carbon leakage as a result of unilateral mitigation policies in different regions. As the EU ETS is the most comprehensive example of such policies, most of the papers focus on examining the impacts of EU ETS on different sectors in various European countries. For instance, (Petrick et al. 2014; Koch and Basse Mama 2019) examined the impacts of EU ETS on 43 German manufacturing plants; (Branger et al. 2017; Boutabba and Lardic 2017)– on cement and steel industry; (Jaraite-Kažukauske and Di Maria 2016) – on Lithuanian manufacturing plants; (Healy et al. 2018) – on cement and aluminium. Neither sectoral-level nor firm-level analysis (primarily for Germany and France) shows any significant evidence of carbon leakage *(robust evidence, medium agreement).*

No significant evidence of carbon leakage was revealed either in the literature that concern situations outside ETS: (Martin et al. 2014) tested carbon leakage as the result of the UK Climate Change Levy (CCL) implementation; (Rivers and Schaufele 2015) looked at the effects of carbon tax on agriculture in British Columbia; (Flues and Lutz 2015) examined the effects of electricity tax on German plants *(robust evidence, low agreement).*

However, this does not necessarily mean that carbon leakage will not occur in EU ETS in future. (Joltreau and Sommerfeld 2019) state that no carbon leakage was revealed in *ex post* literature because of: 1) free allocation of emissions allowances in the first two Phases of EU ETS; 2) over-allocation of allowances during all the 3 Phases of EU ETS; 3) ability of firms in some regulated sectors to pass-through the costs of the EU ETS onto customers. This ability is especially high in power sector, refining and iron-and-steel where the market competition is limited; on the contrary, this ability is relatively low in some sub-sectors from the chemical and from the pulp and paper industry, due to high international competition.

The launch of a set of Pilot regional ETS in China gave another important case for studying carbon leakage. Emissions spillover effects in Chinese economy are remarkable (Zhang 2017) and are the largest for the production of electricity and heat and for heavy industries (Ning et al. 2019). (Tan et al. 2018) reveal significant carbon leakage as a result of the launch of Pilot ETS in Hubei province. Interesting result is that though power & heat sector is usually considered as largely immobile across regions, it showed the largest rate of carbon leakage followed by smelting, non-metallic products and chemical industries *(limited evidence, high agreement)*. The authors explain it with the fact that leakage of production in other energy-intensive sector led to the rise of the demand for electricity.

Earlier e*x ante* modelling studies have generally suggested lower carbon leakage rates (IPCC AR5), yet the most recent sectoral modelling studies seem to suggest higher carbon leakage rates (Limited evidence, Medium agreement). (Carbone and Rivers 2017) come to conclusion that policies designed to reduce emissions by 20% would reduce output in energy-intensive trade-exports sectors by 5% and exports, by 7%, though the modelling results are highly dependent on modelling assumptions. (Antimiani et al. 2016) use a dynamic CGE model to assess the rate of carbon leakage and impacts on competitiveness in a number of scenarios for 2010–2050. They come to conclusion that unilateral EU climate policies will lead to the significant carbon leakage, especially for basic metals, non-metallic minerals and chemicals. For instance, unilateral climate policy would lead to the reduction of exports of basic metals by nearly 25% compared to BAU scenario by 2050.

12.6.3.2 The spillover effects on the energy sector

Trade-related spillovers of mitigation policies include their effect on energy prices. The decrease of demand for fossil fuels 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 spillovers 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 spillover 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 week green paradox but the strong green paradox occurs only for capacity expansion.

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 spillovers 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. (Orlov and Aaheim 2017) predict that if the Paris Agreement parties fulfil their NDC targets, that would result in 1.8% welfare loss in Russia by 2030, primarily due to fossil fuel exports reduction. Domestic consumption of fossil fuels is anticipated to increase that provokes carbon leakage. (Makarov et al. 2017) show that the fulfilment of Paris Agreement parties of their NDCs would lead to 25% reduction of Russia's energy exports by 2030 that would be reflected in the annual reduction of GDP growth rate by 0.2–0.3 percentage points in 2020–2030. Comprehensive diversification policies may mitigate welfare losses to significant extent.

12.6.3.3 The knowledge and technology spillovers

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 spillovers 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 spillover 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 spillovers 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).

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 spillovers 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 flows and related spillover effects at sectoral level

This sub-section provides a cross-sectoral perspectives on finance as enabler or a barrier for GHG mitigation, and will be closely coordinated with Chapter 15.

There is clear lack of in depth peer-reviewed literature addressing the cross-sectoral perspectives of mitigation finance particularly in relation to enabling deep mitigation pathways. As a result much of our assessment will rely on grey literature and with most focus on energy and land-use sectors.

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 US$ 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 recognizing 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).

Diversion of finance away from fossil fuels into renewables is an important channel for low-carbon transitions. Working Group III of the AR5 (IPCC, 2014) assessed an average annual reduction of investment in fossil fuel extraction, transformation, and transportation of 116 billion US$ to limit warming to 2°C, causing negative implications and adverse effects to countries that rely heavily on the production and exports of fossil fuels *(medium evidence, medium agreement).*

The critical options for energy system transitions identified by the literature that are compatible with the Paris climate objective of well below 2°C include onshore wind, solar PV, electricity storage, nuclear energy, CCS in the power sector, and options to reduce emissions in international transport (Rogelj et al. 2018; REN21 2017; IEA 2019b). The wide-scale implementation of these options to levels consistent with achieving 1.5°C is assessed by the IPCC SR1.5 as of medium feasibility. The IPCC SR1.5 further identified investment and finance as key enablers/risks affecting the speed and feasibility of such energy system transition. Two types of such risks relate to the undesirable investment locked-in during the transition and to the scale of finance needed to bring in the desirable investment during the transition (Rogelj et al. 2018). A recent report by Carbon Tracker estimated that US$ 1.6 trillion of capex in locked-in energy assets under the IEA New Policy Scenario (NPS) over the period 2018–2025 would be at risk if the world were to follow the well below 2°C (B2DS) IEA scenario. In contrast, the report estimates that meeting energy demand during the transition would still require very significant investment amounting to US$ 3.3 trillion in B2DS and US$ 4.8 trillion in the NPS over the period 2018–2025 (Carbon Tracker Initiative 2018) *(limited evidence, medium agreement).*

Green bonds and fossil divestment are increasingly recognised as an important approach to climate action within the business community. Recent pledges by large banks and institutional investors give a boost to low carbon transition and are expected to lead to large shifts in finance away from fossil fuel industry into alternatives (Glomsrod and Wei, 2018; Bergman, 2018; Dunlop et al, 2019) *(medium evidence, medium agreement)*. An example is the signing of around 130 international banks at the recent September 2019 UN climate change summit in New York to the Principles for Responsible Banking, which promise to support the implementation of the Paris Agreement by decreasing hydrocarbon investment while promoting renewables (Climate Week NYC 2019).

Agriculture, forestry, and other forms of land use are promising sectors for leveraging financing solutions to scale up GHG mitigation efforts beyond fossil fuel divestment. In that respect there is an urgent need to identify changes in public support that can help to drive scaled-up private sector investment in land use mitigation and adaptation. Such changes may include design of land use mitigation and adaptation strategies, coordination between public and private instruments across land-use sectors, and leveraging of domestic and financial instruments to redirect finance toward greener land-use practices. 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) *(limited evidence, medium agreement).*

In contrast, other literature has criticised the over concentration of climate finance from OECD flowing to developing countries on renewables compared to other crucial forms of clean energy such as energy efficiency and Carbon Capture, Usage and Storage (CCUS), thus undermining national circumstances and important areas of potentials for sustainable development in eligible fossil fuel-intensive emerging economies and developing countries (Warren 2019). One cited macroeconomic transitional risk of such movement is the removal of financial support for hydrocarbon companies in developing countries, for which oil, gas and coal will remain the main sources of energy for the next two decades, leading to negatively jeopardizing national development and energy security. A further related cross-sectoral financial risk during the energy transition explored in the recent financial literature is the risk related to credit quality of heavily carbon-intensive companies (Devalle et al. 2017; Trinks et al. 2017; Trucost ESG Analysis 2019; Oikonomou et al. 2014). The results from this later literature are so far not conclusive showing that credit quality shifts could be positive or negative for companies in high-emitting industries, which in turn may suggest credit implications for opportunities and strategic alignment with energy transition can outweigh the effects of risks involved *(medium evidence, low agreement).*

Spillover and cross-border effects related to climate finance are important source of cross-sector and cross-country mitigation and adaptation activities. Roman et al, 2018 studied the global distribution of the economic impacts associated with financial flows related to 17 different mitigation options and 9 different adaptation options, and confirmed that spillover effects generated by climate finance account on average for 29% of the economic benefits of climate actions linked to those options flow to countries different from the recipient country *(limited evidence, medium agreement).*

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). Some of the innovative alternatives to address the climate financing gap include public-private partnerships (Jensen and Dowlatabadi 2018) and the use of spillover tax revenue from developments generated by earlier mitigation activities , such as clean energy supply, to incentivise the finance of new mitigation projects (Yoshino et al. 2019).

New financing models and approaches are needed to leverage cross-sectoral synergies and manage trade-offs *(limited evidence, high agreement).* The World Bank group and the International Financial Corporation (IFC) have recently introduced a new and innovative approach to climate financing that addresses institutional, infrastructure, and service needs across sectors targeting developing countries and marginalized communities (GPRBA 2019; IDA 2019). The approach is called Result-based Blended Finance (RBBF) and is meant to strengthen accountability through result-based verifiable performance coupled with blending of scarce public funding with private sector commercial capital to realize high impact climate-smart financing of investments across sectors. The International Development Association (IDA) of the World Bank Group has established the Blended Finance Facility (BFF) to enable IFC to mitigate various financial risks associated with climate investments in SMEs, agribusiness, food security, water, and energy infrastructure across sectors to unlock private capital to support projects that are not yet able to meet fully commercial financing terms but promise to be sustainable and have strong development impacts.

12.7 Cross-sectoral perspectives on governance in the context of sustainable development

Effectively responding to climate change while advancing sustainable development will require coordinated efforts among a diverse set of actors on multiple levels (global, national and sub-national). 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). Under the Paris Agreement governments and formal policymaking arrangements still take central role. Yet, the emerging paradigm of 'polycentric climate governance' highlights the growing role of sub-national and non-state actors like cities, NGOs, and companies, and their decisive role in experimentation, norm building, self-regulation, and knowledge diffusion (Jordan et al. 2015; Dorsch and Flachsland 2017). In this report, Chapters 1, 13, 14 and 17 conceptually elaborate governance arrangements in the context of sustainable development.

Due to limited empirical evidence 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). This section addresses the following questions: (i) how specific governance arrangements in domains that cut through traditional sectors – like carbon dioxide removal, the food system, and land-based mitigation – need to be working in order to facilitate agreed policy objectives; (ii) how these domain-specific regimes can enable effective and equitable implementation of policies and measures at all levels; (iii) and how they can address synergies and trade-offs among actions to deliver climate mitigation in the context of sustainable development?

12.7.1 Carbon Dioxide Removal (CDR)

Both 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 and to achieve a balance between anthropogenic emissions by sources and removal by sinks of GHGs in the second half of this century – are impossible to achieve without CDR (see section 12.3). Therefore, 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). Potential adverse side effects and trade-offs with SDGs need to be taken into account (Dooley and Kartha 2018; Mace et al. 2018; Honegger et al.

2018; Mclaren et al. 2019). Therefore, CDR governance should focus on responsibly incentivising research, development, demonstration and targeted near-term deployment of the most promising options (Lomax et al. 2015; Field and Mach 2017; Bellamy 2018).

Tackling CDR governance challenges will be in many respects similar to those around conventional mitigation options. On the global level, CDR methods other than afforestation currently play a minor role in the view of UNFCCC negotiators (Fridahl 2017). To accelerate CDR, a political commitment to formal integration into climate policy frameworks, project-based market mechanisms, emissions accounting and monitoring, reporting and verification (MRV) is needed, which can build on existing rules and procedures (Honegger and Reiner 2018; Torvanger 2019; Mace et al. 2018). Given the long time periods involved in scaling up and deploying novel technologies and approaches, there are huge challenges to be tackled in research, development and demonstration in order to advance innovation and bring down costs (Nemet et al. 2018).

So far, the scientific and political debate about sustainability risks has mostly focused on ecosystem-based CDR methods (including BECCS), often highlighting negative social and ecological impacts involved with competing land-uses, e.g. on food security, biodiversity or land rights (Buck 2016; Dooley and Kartha 2018). Specific regulations for CDR options posing transboundary risks have so far only been developed in the context of the International Maritime Organization's (IMO) London Convention/London Protocol (LC/LP), which explicitly regulates ocean iron fertilisation and allows parties to govern other marine CDR methods like ocean alkanisation (GESAMP 2019).

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). While niche markets and co-benefits can provide entry points for limited deployment (Cox and Edwards 2019), reaching substantial CDR volumes requires formal integration of CDR into national and sub-national governance frameworks (Mace et al. 2018). Because of its centrality to climate governance this will include target setting (Geden et al. 2019; Mclaren et al. 2019), either explicitly (through dedicated CDR targets) or implicitly (through actor-specific mitigation targets like net-zero or net-negative emissions). Countries with credible net-zero emissions targets (like the United Kingdom or Sweden) have not only started to develop incentive schemes to support CDR research and demonstration to potentially offset 'residual emissions', but also led local governments and companies to integrate CDR methods into their mitigation strategies (Bellamy and Geden 2019).

12.7.2 Food Systems

To support the policies outlined in Section 12.4, food system governance requires an inclusive and transparent structure, and depends on the cooperation of actors in several policy areas, in particular agriculture, nutrition, health, trade, climate, and environment (Bhunnoo 2019; Diercks et al. 2019; iPES Food 2019; Termeer et al. 2018; Kugelberg et al., submitted). 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., submitted). National policies can be complemented – or possibly pioneered – by initiatives at the local level (Rose 2018; Aiking and de Boer 2018). 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 systems may come from technological, social or institutional innovations that start as niches but can potentially lead to rapid changes (El Bilali 2019), including changes in social conventions (Jasny 2018; Benton and Bailey 2019).

Regarding the science-policy interface, consensus is needed for the appropriate level of allocating research to sustainable food and nutrition security, international cooperation as well as public-private partnerships and providing evidence for providing regulatory frameworks for emerging technologies that are ‘robust but flexible, proportionate and transparent’, as well as attempts to reform trade, subsidies, and property rights supporting coordinated policies in the areas of agriculture, health, and environment (IAP 2018).

12.7.3 Land-based Mitigation

The SRCCL outlines four categories of land-based mitigation options with large global potential: (i) afforestation; (ii) reforestation and forest restoration; (iii) BECCS; and (iv) biochar addition to soil. These measures can be combined (e.g., afforestation can later serve the purpose to provide biomass for BECCS and/or production of biochar that is added to soils). Section 12.5 in addition included mitigation options that are commonly not designated land-based, but may still be associated with significant land occupation and associated direct/indirect impacts.

The design of policies, institutions, and governance systems can enable opportunities available in the land sector for adaptation and mitigation while providing the basis for sustainable and climate-resilient low-carbon development. Coherent climate and land policy portfolios have the potential to save resources and also amplify social resilience, ecological restoration, and local stakeholder engagement and collaboration between multiple stakeholders.

Regulations can protect people and land, as well as create revenue and encourage investment to rehabilitate degraded lands and invest in net-zero-carbon energy sources. Institutions and policies, which ensure dignified livelihoods and shore people up against instability and poverty can manage the trade-offs in a just transition. Policies promoting the target of land degradation neutrality (LDN) can also support food security, human wellbeing, while delivering climate change mitigation and adaptation (Smith et al. 2019b). Achievement of LDN targets will require a combination of governance approaches, including enabling policy that creates incentives for sustainable land management (such as security of land access, that may require tenure reform), and a platform for integrated land use planning, to facilitates simultaneous consideration of production and conservation objectives (Cowie et al. 2018).

Land policies affect land tenure security and thus the range of options and incentives available for mitigation and adaptation. Purposefully designed policy can provide stability that helps reduce disruptions to people’s food and livelihood security. Policy packages can better than single policy approaches address the complex challenges of sustainable land management and climate change

12.7.4 Additional Cross-Sectoral Perspectives

- Briefly highlighting some common governance issues in 12.7.1/2/3 (e.g. land-use)
- Highlighting common cross-sectoral governance issues arising from sectoral Chapters (6-11)
- Insights from literature on cross-sectoral governance (with focus on SD)
- Institutional feasibility of cross-sectoral governance (common barriers and possible enablers)

12.8 Frequently Asked Questions

FAQ 12.1 How do Direct Air Carbon Capture and Storage, Enhanced Mineral Weathering, Ocean Alkalinisation and Ocean Fertilisation contribute to climate change mitigation?

Direct air capture and carbon storage (DACCS) uses chemical bonding to remove dilute CO_2 directly from ambient air, removes the CO_2 from the sorbent where it is then 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 (as they become exposed to the atmosphere through geological weathering), the comminution of these rocks to increase the surface area, and the spreading of these crushed rocks on soils (or elsewhere) so that they absorb atmospheric CO_2. Ocean Alkalinisation involves the extraction, processing, and dissolution of minerals and addition to the ocean where it enhances chemical transformation of CO_2 and sequestration as bicarbonate and carbonate ions (HCO_3^-, CO_3^{2-}) in the ocean. Ocean Fertilisation involves fertilising the seawater with iron, which speeds up the growth of phytoplankton that take up CO_2, some of which sink into the Deep Ocean and store carbon when the organisms die.

FAQ 12.2: Why is it important to assess mitigation measures systemically, rather than only looking at their potential to reduce GHG emissions?

Mitigation measures do not only reduce GHGs, but have wider impacts. They can result in decreases or increases GHG emissions in another sector or part of the value chain to where they are applied. They can also have wider environmental, social and economic co-benefits or adverse side effects. Taking these considerations into account can help to enhance the benefit of mitigation action, and avoid unintended consequences. They can also provide a stronger case for achieving political and societal support and raising the finances required for implementation.

FAQ 12.3: What is the difference between GHG emissions from agriculture and GHG emissions from food systems?

The current system for estimating GHG emissions is structured into economic sectors, and agriculture is one of them. Food produced from agriculture, however, serves to feed people with food that satisfies dietary requirements. On the way from the farm to the mouth a lot may happen: food is transported, processed, lost and wasted, packed, distributed, cooked. Food waste has to be managed and inputs to the food system industries have to be supplied. Looking at the food system as a whole connects each citizen to total GHG emissions his or her diet is causing. But more importantly, a food system approach opens the door for additional mitigation opportunities, for example improving the circularity of the biomass and providing alternatives to food with high GHG emissions. It also makes trade-offs transparent and thus helps making better choices.

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

The following tables (SM 12.A Table 1 and SM 12.A Table 2) present examples of the information used in the construction of Figure 12.10. SM 12.A Table 1 provides examples of mitigation actions that fall into the groups of actions shown Figure 12.10 in the different sectors. Note that the mapping is intended to be illustrative and is not intended to be exhaustive.

SM 12.A 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 optimizations, 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 **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. 2019a)
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.A 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 12-14.

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) (Smith et al. 2019a) 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) (Ürge-Vorsatz et al. 2014).	
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) (Åhman et al. 2017).
IV. Employment	Job opportunities can be created in energy efficiency, AFOLU and renewable energy actions (A, D, E) (Smith et al. 2019a)	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 dependant 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 (BDE)	
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 (BEDFG)	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 (BEFG)	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) (Smith et al. 2019a).	Reducing deforestation could lead to reduced energy access for those dependant 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) (Kerr et al. 2017) Afforestation can provide increased access to firewood and protection of diversity which can lead to positive economic outcomes (D) (Smith et al. 2019a). 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 dependant 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. 2019a) 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) (Buonocore et al. 2016; Ürge-Vorsatz et al. 2014). 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) (Ürge-Vorsatz et al. 2014).	
XIII. Political stability, democracy	Integrated planning approaches which include climate mitigation considerations can support political stability and democracy in decision making (C)	

Cross Chapter Appendix on Biomass

Introduction

This Biomass Appendix deals with biomass use for bioenergy and BECCS as well as other non-food biomass uses. It builds on previous special reports (SRREN, SR1.5, SRCCL) and assessments (AR5-WG3), and will draw on assessment made in several chapters of this assessment report (AR6-WG3). Three topics will be covered:

- The climate change mitigation effects of bioenergy and other biobased systems, considering also the associated land use and land use change;
- Deployment of bioenergy, BECCS and other biobased options in 1.5°C /2°C pathways; and
- The biomass demands for bioenergy and other biobased applications in 1.5°C /2°C pathways, compared with estimates of future availability of biomass resources

SRREN (IPCC 2012) provided a comprehensive overview on bioenergy (Chum et al. 2012). A specific bioenergy Appendix was included in the WGIII AR5 report (Smith et al. 2014) recognising that many of the more stringent mitigation scenarios presented in this report (resulting in 450 ppm, but also 550 ppm CO_2-eq concentration by 2100) relied heavily on large-scale deployment of BECCS, and a large body of literature published since SRREN complemented and updated the analysis presented in SRREN.

The SR1.5 extended the AR5 mitigation pathway assessment based on new scenario literature. All analysed pathways limiting warming to 1.5°C with no or limited overshoot were found to use CDR to some extent to neutralize emissions from sources for which no mitigation measures have been identified and, in most cases, also to achieve net negative emissions to return global warming to 1.5°C following an overshoot (Rogelj et al. 2018). Some pathways relied more on BECCS, while others relied more on afforestation, which were the two CDR methods most often included in integrated pathways modelled for SR1.5. Bioenergy use was substantial in 1.5°C pathways with or without BECCS due to its multiple roles in decarbonizing energy use (full range: 40–310 EJ yr^{-1}, primary energy, in 2050; Rogelj et al. 2018).

The SRCCL report (IPCC 2019) found that implementation of mitigation response options, limiting warming to 1.5°C or 2°C, would require conversion of large areas of land for afforestation/ reforestation and bioenergy crops. The change of global forest area in mitigation pathways ranges from about –0.2 to +7.2 Mkm^2 between 2010 and 2100 (median values across a range of models and scenarios: RCP4.5, RCP2.6, RCP1.9), and the land demand for bioenergy crops ranges from about 3.2 to 6.6 Mkm^2 in 2100 (Shukla et al. 2019). For comparison, 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 (some 21 Mkm^2 of savannahs and shrublands are also used for grazing) (IPCC 2019).

Biomass can be used for mitigation in several other applications, such as replacing cement in construction, using carbon fibers as a substitute for steel, and using biobased plastics, chemicals, clothing, and packaging. Biomass can also be used to produce biochar providing carbon storage through incorporation into soil. Such mitigation options have not yet been widely incorporated into the integrated assessment models (IAMs) that provide the scenario literature included in IPCC assessments. Further, afforestation has mostly been included as a CDR-only option that is not assumed to provide biomass to society. In this regard, land use for biomass production and for carbon storage have been modelled as mutually exclusive mitigation options.

The climate change mitigation effects of bioenergy and other biobased systems

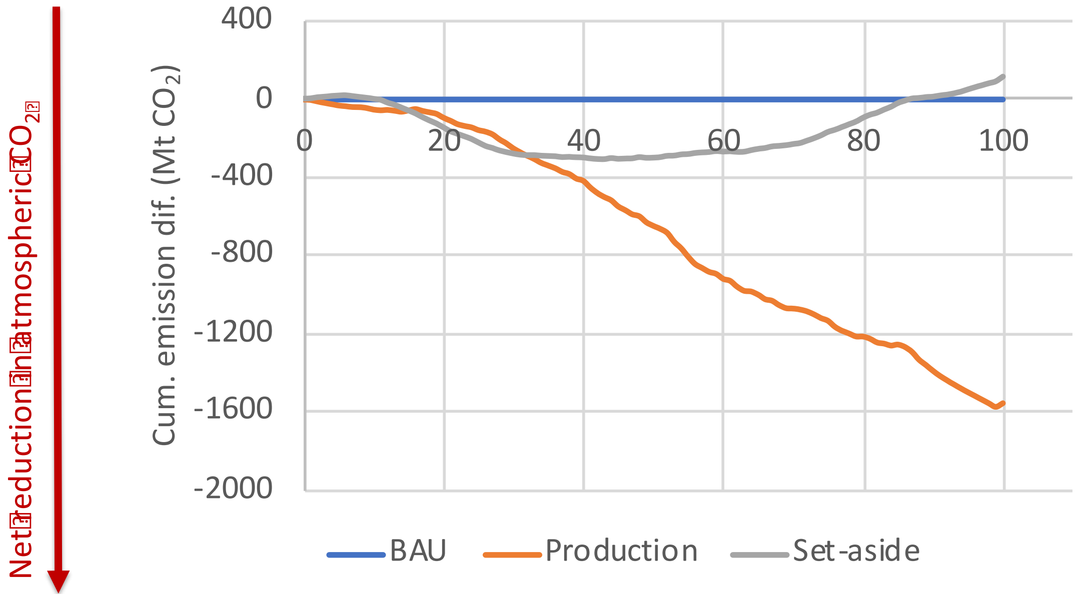
The net GHG effects of using biomass depend on: (i) how much GHG emissions are avoided when the biomass is used instead of coal, petroleum, metals, and other resources; and (ii) how the biomass use – and the associated land use – influence the amount of carbon that is stored in soils, vegetation, and in biobased products over time. Long-lived biobased products such as construction timber store carbon for a longer time than short-lived biobased products, such as newspaper and biofuels. Re-use and recycling can extend the carbon storage time and – eventually – combustion with energy recovery (displacing other energy supply) and BECCS can enhance the mitigation value further.

The GHG effects of using biomass can be quantified with different methods. One approach is to quantify and compare GHG emissions associated with the biobased product and with the alternative product assumed to be replaced. The quantifications are commonly made based on life cycle assessment (LCA). International Standards for the implementation of LCA provide guidelines and a framework for assessment, and several requirements and recommendations to increase the comparability of LCAs having equivalent assumptions and contexts. A brief info section– *Estimating potential mitigation effects associated with the use of biomass as material and for energy* – is planned to cover the following:

- LCA climate change impact category as methodological basis for assessing the GHG-mitigation potential of defined functional units (e.g., bioenergy or building products)
- requirements for conducting product LCA in line with current standards (14040/44 & ISO 21930 etc.).
- Estimating potential GHG impact on national scale by combining LCA results of defined functional units with relevant statistics reflecting the domestic consumption of those functional units and their substitutes (e.g. wooden and conventional buildings) + examples
- Consistent quantification of GHG implications associated with the biogenic carbon content of biomass as material inherent property (IPCC 2019 Refinement Ch12)
- Assessing the GHG mitigation potential of biomass use on the basis of substantiated scenarios of market development of functional units, reflecting the biomass use and their conventional /fossil-based substitutes in comparison with a defined ‘business as usual’ scenario + examples
- Relevance and limitations of GHG substitution factors and influence of temporal and spatial system boundaries on assessment outcome.

Complementary to this, a selection of 1.5°C/2°C pathways will be described in terms of dynamic land carbon losses and gains (AFOLU) and transfer of biogenic carbon to geological storages through BECCS. Trade-offs between biomass production, carbon sequestration, and storage of carbon in vegetation, soils, and biobased products will be discussed, considering objectives to reduce near term warming and achieving longer-term temperature stabilization.

Biomass Annex Figure 1 is an example of how this trade-off can be presented. The diagram illustrates how the net carbon emissions to the atmosphere can change when forest management strategies are changed. The harvested biomass is in these scenarios used for buildings, pulp/paper, combined heat and power, and/or biofuels for transport. The GHG effects of forest management and biomass use result from carbon storage in forests and biobased products, and from GHG savings associated with product substitution. Please see the note in Figure caption.



Biomass Annex Figure 1 Differences in cumulative CO_2 emissions ($MtCO_2$) resulting from different management strategies over a period of 100 years. A Business-as-usual scenario (BAU), here set to 0, is compared with a Production scenario, including introduction of silvicultural measures to increase forest growth, and a Set-aside scenario doubling the area of set-aside land compared to BAU.

Note: the diagram is only intended to illustrate how different forest management strategies can yield different outcomes. It should not be understood as being generally valid across the world. The outcome depends on forest characteristics, forest management practices, and GHG savings associated with the forest product mix. All of these factors differ from one location to another.

Beyond GHGs, a summary will be provided of recent literature covering the influence of land use on climate through: (i) modulating the share of incoming radiation that is reflected into space (i.e., changing the albedo); (ii) influencing hydrology and evapotranspiration, which in turn influences the near-surface temperatures; and (iii) influencing the emission of biogenic volatile organic compounds, which in turn influences the formation of aerosols in the atmosphere. The net effect of all the climate forcers combined is uncertain and location-specific, although studies have shown that the effects of non-GHG forcers can be as large as those of GHGs. The SR1.5 report concluded that the biophysical impacts of land-use changes are important to assess in the context of 1.5°C /2°C pathways, especially pathways towards 1.5°C warming levels (Hoegh-Guldberg et al. 2018).

Few IAMs include biophysical feedback processes. A relatively small segment of the modelling literature combines IAMs with earth system type models to capture the full suite of climate forcings. These indicate that the mitigation effect of bioenergy, BECCS and most other land-based options will depend on the geography of the associated land use and land use change. For example, land clearing, especially forest clearing, results in (i) increased warming due to GHG emissions, and (ii) changes in albedo and energy exchange characteristics, which result in surface air warming in the tropical regions and cooling in temperate and polar regions.

Deployment of bioenergy, BECCS and other biobased options in 1.5°C/2°C pathways

The deployment of bioenergy, BECCS and other biobased systems depends, inter alia, on the costs of these options compared with cost of alternative options that do not use biomass. Dispatchable biobased power could play an important role in efficient integration of variable renewable electricity in the future. But other balancing power options, various types of demand side management, and storage systems, can limit the need for biobased balancing power. Biofuels, electrification, and vehicle energy efficiency are commonly expected to provide rapid and deep reductions in fossil fuel use in the transport sector. Here, the role of biofuels depends on the pace of road transport electrification and also on development of alternatives in aviation and long distance shipping.

Biomass may be increasingly used in BECCS applications, which will compete with other CDR options and with other uses of biomass. The SR1.5 report (Rogelj et al. 2018) found that, typically, if bioenergy is strongly limited, BECCS options with high capture rates are favoured. If bioenergy is plentiful, IAMs tend to choose biofuel options with lower capture rates but high value for replacing fossil fuels in transport. Most bioenergy use in IAMs is combined with CCS if available. If CCS is unavailable, bioenergy use remains largely unchanged or even increases due to the high value of bioenergy for energy transformation. High biomass prices may lead to modifications of processes (e.g., electrification) in industries that currently represent large point sources of biogenic carbon emissions and hence BECCS opportunities.

The role of BECCS as a dominant CDR measure in deep mitigation pathways has been reduced since the time of the AR5, due to (i) a broader range of underlying assumptions about socio-economic drivers and associated energy and food demand; (ii) incorporation of a larger portfolio of mitigation and CDR options; and (iii) targeted analysis of deployment limits for specific CDR options, such as BECCS, A/R, biochar, and soil carbon management. The prevalence of bioenergy and BECCS in IAMs might become further reduced as additional CDR options are built into IAMs. A few options, namely biochar and carbon storage in wood houses and other long-lived biobased products, can have a double influence on bioenergy/BECCS deployment by competing for biomass resources. At the same time, as increasingly detailed representation of CDR options in IAMs yields new insights, expectation on bioenergy and BECCS might also be revised upwards due to an apparent attractiveness relating to various societal objectives.

As for energy applications, the attractiveness of biobased materials will depend on whether alternative materials can reduce their carbon footprint. In that regard, development of climate friendly basic materials such as concrete, iron and steel, can have large implications for the future demand for biomass for material applications. On the other hand, as measures to reduce GHG emission in cement, iron and steel production commonly involve the use of biomass (as process fuel and reducing agent), the biomass demand related to building and infrastructure expansion may anyway increase significantly. For context, estimates by the UNEP International Resource Panel indicate that urban infrastructure will almost double by 2050 (IRP 2018).

The Biomass Appendix will build on SR1.5 and assessments in AR6-WG3 to provide a summary on current state of knowledge concerning deployment of bioenergy, BECCS and biobased options in 1.5°C/2°C pathways. As biobased applications other than bioenergy are not yet been widely incorporated into the IAMs, it is expected that this summary will to a significant degree rely on assessment results in the sectoral chapters in AR6-WG3.

The size of biomass demand for bioenergy and other biobased applications in 1.5°C/2°C pathways, compared with estimates of future availability of biomass resources

The final part of the Biomass Appendix will summarize the findings in previous IPCC reports and in this report, concerning biomass demand for bioenergy and other biobased applications in 1.5°C/2°C pathways. This will be compared with estimates of future availability of biomass resources, as reported in AR6-WG3 Chapter 7.

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