6

Interlinkages between desertification, land degradation, food security and greenhouse gas fluxes: Synergies, trade-offs and integrated response options

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Table of contents

Executive summary

The land challenges, in the context of this report, are climate change mitigation, adaptation, desertification, land degradation, and food security. The chapter also discusses implications for Nature's Contributions to People (NCP), including biodiversity and water, and sustainable development, by assessing intersections with the Sustainable Development Goals (SDGs). The chapter assesses response options that could be used to address these challenges. These response options were derived from the previous chapters and fall into three broad categories: land management, value chain, and risk management.

The land challenges faced today vary across regions; climate change will increase challenges in the future, while socio-economic development could either increase or decrease challenges (*high confidence*). Increases in biophysical impacts from climate change can worsen desertification, land degradation, and food insecurity (*high confidence*). Additional pressures from socio-economic development could further exacerbate these challenges; however, the effects are scenario dependent. Scenarios with increases in income and reduced pressures on land can lead to reductions in food insecurity; however, all assessed scenarios result in increases in water demand and water scarcity (*medium confidence*). {6.1}

The applicability and efficacy of response options are region and context specific; while many value chain and risk management options are potentially broadly applicable, many land management options are applicable on less than 50% of the ice-free land surface (*high confidence*). Response options are limited by land type, bioclimatic region, or local food system context (*high confidence*). Some response options produce adverse side effects only in certain regions or contexts; for example, response options that use freshwater may have no adverse side effects in regions where water is plentiful, but large adverse side effects in regions where water is scarce (*high confidence*). Response options with biophysical climate effects (e.g., afforestation, reforestation) may have different effects on local climate, depending on where they are implemented (*medium confidence*). Regions with more challenges have fewer response options available for implementation (*medium confidence*). {6.1, 6.2, 6.3, 6.4}

Nine options deliver medium-to-large benefits for all five land challenges (*high confidence*). The options with medium-to-large benefits for all challenges are increased food productivity, improved cropland management, improved grazing land management, improved livestock management, agroforestry, forest management, increased soil organic carbon content, fire management and reduced post-harvest losses. A further two options, dietary change and reduced food waste, have no global estimates for adaptation but have medium-to-large benefits for all other challenges (*high confidence*). {6.3, 6.4}

Five options have large mitigation potential (>3 $GtCO_2e\ yr^{-1}$) without adverse impacts on the other challenges (*high confidence*). These are: increased food productivity; reduced deforestation and forest degradation; increased soil organic carbon content; fire management; and reduced post-harvest losses. Two further options with large mitigation potential, dietary change and reduced food waste, have no global estimates for adaptation but show no negative impacts across the other challenges. Five options: improved cropland management; improved grazing land managements; agroforestry; integrated water management; and forest management, have moderate mitigation potential, with no adverse impacts on the other challenges (*high confidence*). {6.3.6}

Sixteen response options have large adaptation potential (more than 25 million people benefit), without adverse side effects on other land challenges (*high confidence*). These are increased food productivity, improved cropland management, agroforestry, agricultural diversification, forest management, increased soil organic carbon content, reduced landslides and natural hazards, restoration and reduced conversion of coastal wetlands, reduced post-harvest losses, sustainable sourcing, management of supply chains, improved food processing and retailing, improved energy use in food systems, livelihood diversification, use of local seeds, and disaster risk management (*high confidence*). Some options (such as enhanced urban food systems or management of urban sprawl) may not provide large global benefits but may have significant positive local effects without adverse effects (*high confidence*). {6.3, 6.4}

Seventeen of 40 options deliver co-benefits or no adverse side effects for the full range of NCPs and SDGs; only three options (afforestation, bioenergy and bioenergy with carbon capture and storage (BECCS), and some types of risk sharing instruments, such as insurance) have potentially adverse side effects for five or more NCPs or SDGs (*medium confidence*). The 17 options with co-benefits and no adverse side effects include most agriculture- and soil-based land management options, many ecosystem-based land management options, forest management, reduced post-harvest losses, sustainable sourcing, improved energy use in food systems, and livelihood diversification (*medium confidence*). Some of the synergies between response options and SDGs include positive poverty eradication impacts from activities like improved water management or improved management of supply chains. Examples of synergies between response options and NCPs include positive impacts on habitat maintenance from activities like invasive species management and agricultural diversification. However, many of these synergies are not automatic, and are dependent on well-implemented activities requiring institutional and enabling conditions for success. {6.4}

Most response options can be applied without competing for available land; however, seven options result in competition for land (*medium confidence*). A large number of response options do not require dedicated land, including several land management options, all value chain options, and all risk management options. Four options could greatly increase competition for land if applied at scale: afforestation, reforestation, and land used to provide feedstock for BECCS or biochar, with three further options: reduced grassland conversion to croplands, restoration and reduced conversion of peatlands and restoration, and reduced conversion of coastal wetlands having smaller or variable impacts on competition for land. Other options such as reduced deforestation and forest degradation, restrict land conversion for other options and uses.

6

Expansion of the current area of managed land into natural ecosystems could have negative consequences for other land challenges, lead to the loss of biodiversity, and adversely affect a range of NCPs (*high confidence*). {6.3.6, 6.4}

Some options, such as bioenergy and BECCS, are scale dependent. The climate change mitigation potential for bioenergy and BECCS is large (up to 11 $GtCO_2$ yr^{-1}); however, the effects of bioenergy production on land degradation, food insecurity, water scarcity, greenhouse gas (GHG) emissions, and other environmental goals are scale- and context-specific (*high confidence*). These effects depend on the scale of deployment, initial land use, land type, bioenergy feedstock, initial carbon stocks, climatic region and management regime (*high confidence*). Large areas of monoculture bioenergy crops that displace other land uses can result in land competition, with adverse effects for food production, food consumption, and thus food security, as well as adverse effects for land degradation, biodiversity, and water scarcity (*medium confidence*). However, integration of bioenergy into sustainably managed agricultural landscapes can ameliorate these challenges (*medium confidence*). {6.2, 6.3, 6.4, Cross-Chapter Box 7 in this chapter}

Response options are interlinked; some options (e.g., land sparing and sustainable land management options) can enhance the co-benefits or increase the potential for other options (*medium confidence*). Some response options can be more effective when applied together (*medium confidence)*; for example, dietary change and waste reduction expand the potential to apply other options by freeing 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) of land (*low confidence*). Integrated water management and increased soil organic carbon can increase food productivity in some circumstances. {6.4}

Other response options (e.g., options that require land) may conflict; as a result, the potentials for response options are not all additive, and a total potential from the land is currently unknown (*high confidence*). Combining some sets of options (e.g., those that compete for land) may mean that maximum potentials cannot be realised, for example, reforestation, afforestation, and bioenergy and BECCS, all compete for the same finite land resource so the combined potential is much lower than the sum of potentials of each individual option, calculated in the absence of alternative uses of the land (*high confidence*). Given the interlinkages among response options and that mitigation potentials for individual options assume that they are applied to all suitable land, the total mitigation potential is much lower than the sum of the mitigation potential of the individual response options (*high confidence*). {6.4}

The feasibility of response options, including those with multiple co-benefits, is limited due to economic, technological, institutional, socio-cultural, environmental and geophysical barriers (*high confidence*). A number of response options (e.g., most agriculture-based land management options, forest management, reforestation and restoration) have already been implemented widely to date (*high confidence*). There is robust evidence that many other response options can deliver co-benefits across the range of land challenges, yet these are not being implemented. This limited application is evidence that multiple barriers to implementation of response options exist (*high confidence*). {6.3, 6.4}

Coordinated action is required across a range of actors, including business, producers, consumers, land managers, indigenous peoples and local communities and policymakers to create enabling conditions for adoption of response options (*high confidence*). The response options assessed face a variety of barriers to implementation (economic, technological, institutional, socio-cultural, environmental and geophysical) that require action across multiple actors to overcome (*high confidence*). There are a variety of response options available at different scales that could form portfolios of measures applied by different stakeholders – from farm to international scales. For example, agricultural diversification and use of local seeds by smallholders can be particularly useful poverty eradication and biodiversity conservation measures, but are only successful when higher scales, such as national and international markets and supply chains, also value these goods in trade regimes, and consumers see the benefits of purchasing these goods. However, the land and food sectors face particular challenges of institutional fragmentation, and often suffer from a lack of engagement between stakeholders at different scales (*medium confidence*). {6.3, 6.4}

Delayed action will result in an increased need for response to land challenges and a decreased potential for land-based response options due to climate change and other pressures (*high confidence*). For example, failure to mitigate climate change will increase requirements for adaptation and may reduce the efficacy of future land-based mitigation options (*high confidence*). The potential for some land management options decreases as climate change increases; for example, climate alters the sink capacity for soil and vegetation carbon sequestration, reducing the potential for increased soil organic carbon (*high confidence*). Other options (e.g., reduced deforestation and forest degradation) prevent further detrimental effects to the land surface; delaying these options could lead to increased deforestation, conversion, or degradation, serving as increased sources of GHGs and having concomitant negative impacts on NCPs (*medium confidence*). Carbon dioxide removal (CDR) options – such as reforestation, afforestation, bioenergy and BECCS – are used to compensate for unavoidable emissions in other sectors; delayed action will result in larger and more rapid deployment later (*high confidence*). Some response options will not be possible if action is delayed too long; for example, peatland restoration might not be possible after certain thresholds of degradation have been exceeded, meaning that peatlands could not be restored in certain locations (*medium confidence*). {6.2, 6.3, 6.4}

Early action, however, has challenges including technological readiness, upscaling, and institutional barriers (*high confidence*). Some of the response options have technological barriers that may limit their wide-scale application in the near term (*high confidence*). Some response options, for example, BECCS, have only been implemented at small-scale demonstration facilities; challenges exist with upscaling these options to the levels discussed in this Chapter (*medium confidence*). Economic and institutional barriers, including governance, financial incentives and financial resources, limit the near-term adoption of many response options, and 'policy lags', by which implementation is delayed by the slowness of the policy implementation cycle, are significant across many options (*medium confidence*). Even some actions that initially seemed like 'easy wins' have been challenging to implement, with stalled policies for reducing emissions from deforestation and forest degradation and fostering conservation (REDD+) providing clear examples of how response options need sufficient funding, institutional support, local buy-in, and clear metrics for success, among other necessary enabling conditions. {6.2, 6.4}

Some response options reduce the consequences of land challenges, but do not address underlying drivers (*high confidence*). For example, management of urban sprawl can help reduce the environmental impact of urban systems; however, such management does not address the socio-economic and demographic changes driving the expansion of urban areas. By failing to address the underlying drivers, there is a potential for the challenge to re-emerge in the future (*high confidence*). {6.4}

Many response options have been practised in many regions for many years; however, there is limited knowledge of the efficacy and broader implications of other response options (*high confidence*). For the response options with a large evidence base and ample experience, further implementation and upscaling would carry little risk of adverse side effects (*high confidence*). However, for other options, the risks are larger as the knowledge gaps are greater; for example, uncertainty in the economic and social aspects of many land response options hampers the ability to predict their effects (*medium confidence*). Furthermore, Integrated Assessment Models, like those used to develop the pathways in the IPCC Special Report on Global Warming of 1.5°C (SR15), omit many of these response options and do not assess implications for all land challenges (*high confidence*). {6.4}

6.1 Introduction

6.1.1 Context of this chapter

This chapter focuses on the interlinkages between response options[1] to deliver climate mitigation and adaptation, to address desertification and land degradation, and to enhance food security. It also assesses reported impacts on Nature's Contributions to People (NCP) and contributions to the UN Sustainable Development Goals (SDGs). By identifying which options provide the most co-benefits with the fewest adverse side effects, this chapter aims to provide *integrated response options* that could co-deliver across the range of challenges. This chapter *does not consider* response options that affect only one aspect of climate mitigation, adaptation, desertification, land degradation, or food security in isolation, since these are the subjects of Chapters 2–5; this chapter *considers only* interlinkages between response options, and two or more of these challenges in the land sector.

Since the aim is to assess and provide guidance on integrated response options, each response option is first described and categorised, drawing on previous chapters 2–5 (Section 6.2), and their impact on climate mitigation/adaptation, desertification, land degradation, and food security is quantified (Section 6.3). The feasibility of each response option, respect to costs, barriers, saturation and reversibility is then assessed (Section 6.4.1), before considering their sensitivity to future climate change (Section 6.4.2).

The *co-benefits* and *adverse side effects*[2] of each integrated response option across the five land challenges, and their impacts on the NCP and the SDGs, are then assessed in Section 6.4.3. In section 6.4.4, the spatial applicability of these integrated response options is assessed in relation to the location of the challenges, with the aim of identifying which options have the greatest potential to co-deliver across the challenges, and the contexts and circumstances in which they do so. Interlinkages among response options and challenges in future scenarios are also assessed in Section 6.4.4. Finally, Section 6.4.5 discusses the potential consequences of delayed action.

In providing this evidence-based assessment, drawing on the relevant literature, this chapter does not assess the merits of policies to deliver these integrated response options – Chapter 7 assesses the various policy options currently available to deliver these interventions. Rather, this chapter provides an assessment of the integrated response options and their ability to co-deliver across the multiple challenges addressed in this Special Report.

6.1.2 Framing social challenges and acknowledging enabling factors

In this section we outline the approach used in assessing the evidence for interactions between response options to deliver climate mitigation and adaptation, to prevent desertification and land degradation, and to enhance food security. Overall, while defining and presenting the response options to meet these goals is the primary goal of this chapter, we note that these options must not be considered only as technological interventions, or one-off actions. Rather, they need to be understood as responses to socio-ecological challenges whose success will largely depend on external enabling factors. There have been many previous efforts at compiling positive response options that meet numerous SDGs, but which have not resulted in major shifts in implementation; for example, online databases of multiple response options for sustainable land management (SLM), adaptation, and other objectives have been compiled by many donor agencies, including World Overview of Conservation Approaches and Technologies (WOCAT), Climate Adapt, and the Adaptation Knowledge Portal (Schwilch et al. 2012b).[3] Yet, clearly barriers to adoption remain, or these actions would have been more widely used by now. Much of the scientific literature on barriers to implementing response options focuses on the individual and household level, and discusses limits to adoption, often primarily identified as economic factors (Nigussie et al. 2017; Dallimer et al. 2018). While a useful approach, such studies are often unable to account for the larger enabling factors that might assist in more wide-scale implementation (Chapter 7 discusses these governance factors and associated barriers in more detail).

Instead, this chapter proposes that each response option identified and assessed needs to be understood as an intervention within complex socio-ecological systems (SES) (introduced in Chapter 1). In this understanding, physical changes affect human decision-making over land and risk management options, as do economics, policies, and cultural factors, which in turn may drive additional ecological change (Rawlins and Morris 2010). This co-evolution of responses within an SES provides a more nuanced understanding of the dynamics between drivers of change and impacts of interventions. Thus, in discussions of the 40 specific response options in this chapter, it must be kept in mind that all need to be contextualised within the specific SES in which they are deployed (Figure 6.1). Framing response options within SESs also recognises the interactions *between* different response options. However, a major problem within SESs is that the choice and use of different response options requires knowledge of the problems they are aimed at solving, which may be unclear, contested, or not shared equally among stakeholders (Carmenta et al. 2017). Drivers of environmental change often have primarily social or economic, rather than technological roots, which requires acknowledgement that the response options not aimed at reducing the drivers of change may thus be less successful (Schwilch et al. 2014).

1 Many of the response options considered are *sustainable land management* options, but several response options are not based on land management – for example, those based on value chain management and governance and risk management options.

2 We use the IPCC Fifth Assessment Report Working Group III definitions of co-benefits and adverse side effect – see Glossary. Co-benefits and adverse side effects can be biophysical and/or socio-economic in nature, and all are assessed as far as the literature allows.

3 For example, see https://qcat.wocat.net/en/wocat/; https://climate-adapt.eea.europa.eu; https://www4.unfccc.int/sites/NWPStaging/Pages/Home.aspx.

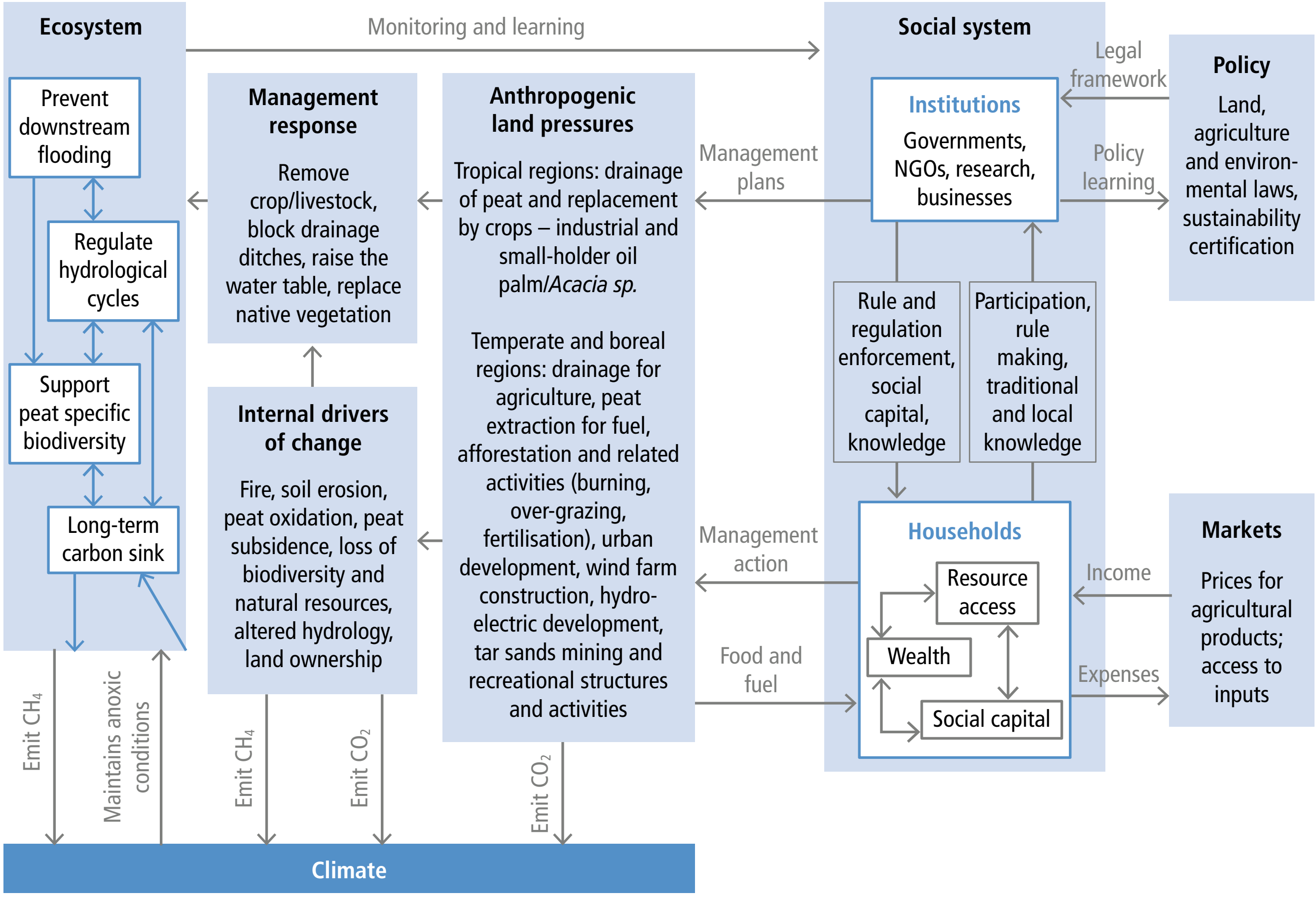

Figure 6.1 | Model to represent a social-ecological system of one of the integrated response options in this chapter, using restoration and reduced impact of peatlands as an example. The boxes show systems (ecosystem, social system), external and internal drivers of change and the management response – here enacting the response option. Unless included in the 'internal drivers of change' box, all other drivers of change are external (e.g., climate, policy, markets, anthropogenic land pressures). The arrows represent how the systems can influence each other, with key drivers of impact written in the arrow in the direction of effect.

Response options must also account for the uneven distribution of impacts among populations of both environmental change and intervention responses to this change. Understanding the integrated response options available in a given context requires an understanding of the specificities of social vulnerability, adaptive capacity, and institutional support to assist communities, households and regions to reach their capabilities and achievement of the SDG and other social and land management goals. Vulnerability reflects how assets are distributed within and among communities, shaped by factors that are not easily overcome with technical solutions, including inequality and marginalisation, poverty, and access to resources (Adger et al. 2004; Hallegate et al. 2016). Understanding why some people are vulnerable, and what structural factors perpetuate this vulnerability requires attention to both micro and meso scales (Tschakert et al. 2013). These vulnerabilities create barriers to adoption of even low-cost high-return response options, such as soil carbon management, that may seem obviously beneficial to implement (Mutoko et al. 2014; Cavanagh et al. 2017). Thus, assessment of the differentiated vulnerabilities that may prevent the adoption of a response option need to be considered as part of any package of interventions.

Adaptive capacity relates to the ability of institutions or people to modify or change characteristics or behaviour so as to cope better with existing or anticipated external stresses (Moss et al. 2001; Brenkert and Malone 2005; Brooks et al. 2005). Adaptive capacity reflects institutional and policy support networks, and has often been associated at the national level with strong developments in the fields of economics, education, health, and governance and political rights (Smit et al. 2001). Areas with low adaptive capacity, as reflected in low Human Development Index scores, might constrain the ability of communities to implement response options (Section 6.4.4.1 and Figure 6.7).

Further, while environmental changes like land degradation have obvious social and cultural impacts, (as discussed in the preceding chapters), so do response options. Therefore, careful thought is needed about what impacts are expected and what trade-offs are acceptable. One potential way to assess the impact of response interventions relates to the idea of capabilities, a concept first proposed by economist Amartya Sen (Sen 1992). Understanding capability as the 'freedom to achieve well-being' frames a problem as being a matter of facilitating what people aspire to do and be, rather than telling them to achieve a standardised or predetermined outcome (Nussbaum and Sen 1993). Thus a capability approach is generally a more flexible and multi-purpose framework, appropriate to an SES understanding because of its open-ended approach (Bockstael and Berkes 2017). Thus, one question for any decision-maker approaching schematics of response options is to determine which response options lead to increased or decreased capabilities for the stakeholders who are the objects of the interventions, given the context of the SES in which the response option will be implemented.

Section 6.4.3 examines some of the capabilities that are reflected in the UN Sustainable Development Goals (SDGs), such as gender equality and education, and assesses how each of the 40 response options may affect those goals, either positively or negatively, through a review of the available literature.

6.1.2.1 Enabling conditions

Response options are not implemented in a vacuum and rely on knowledge production and socio-economic and cultural strategies and approaches embedded within them to be successful. For example, it is well known that "Weak grassroots institutions characterised by low capacity, failure to exploit collective capital and poor knowledge sharing and access to information, are common barriers to sustainable land management and improved food security" (Oloo and Omondi 2017). Achieving broad goals such as reduced poverty or sustainable land management requires conducive enabling conditions, such as attention to gender issues and the involvement of stakeholders, such as indigenous peoples and local communities, as well as attention to governance, including adaptive governance, stakeholder engagement, and institutional facilitation (Section 6.4.4.3). These enabling conditions – such as gender-sensitive programming or community-based solutions – are not categorised as individual response options in subsequent sections of this chapter because they are conditions that can potentially help improve *all* response options when used in tandem to produce more sustainable outcomes. Chapter 7 picks up on these themes and discusses the ways various policies to implement response options have tried to minimise unwanted social and economic impacts on participants in more depth, through deeper analysis of concepts such as citizen science and adaptive governance. Here we simply note the importance of assessing the contexts in which response options will be delivered, as no two situations are the same, and no single response option is likely to be a 'silver bullet' to solve all land–climate problems; each option comes with potential challenges and trade-offs (Section 6.2), barriers to implementation (Section 6.4.1), interactions with other sectors of society (Section 6.4.3), and potential environmental limitations (Section 6.4.4).

6.1.3 Challenges and response options in current and historical interventions

Land-based systems are exposed to multiple overlapping challenges, including climate change (adaptation and mitigation), desertification (Chapter 3), land degradation (Chapter 4) and food insecurity (Chapter 5), as well as loss of biodiversity, groundwater stress (from over-abstraction) and water quality. The spatial distribution of these individual land-based challenges is shown in Figure 6.2, based on recent studies and using the following indicators:

- Desertification attributed to land use is estimated from vegetation remote sensing (Figure 3.7c), mean annual change in NDVImax <–0.001 (between 1982 and 2015) in dryland areas (Aridity Index >0.65), noting, however, that desertification has multiple causes (Chapter 3).
- Land degradation (Chapter 4) is based on a soil erosion (Borrelli et al. 2017) proxy (annual erosion rate of 3 t ha^{-1} or above).
- The climate change challenge for adaptation is based on a dissimilarity index of monthly means of temperature and precipitation between current and end-of-century scenarios (dissimilarity index equal to 0.7 or above; Netzel and Stepinski 2018), noting, however, that rapid warming could occur in all land regions (Chapter 2).
- The food security challenge is estimated as the prevalence of chronic undernourishment (higher or equal to 5%) by country in 2015 (FAO 2017a), noting, however, that food security has several dimensions (Chapter 5).
- The biodiversity challenge uses threatened terrestrial biodiversity hotspots (areas where exceptional concentrations of endemic species are undergoing exceptional loss of habitat, (Mittermeier et al. 2011), noting, however, that biodiversity concerns more than just threatened endemic species.
- The groundwater stress challenge is estimated as groundwater abstraction over recharge ratios above one (Gassert et al. 2014) in agricultural areas (croplands and villages).
- The water quality challenge is estimated as critical loads (higher or equal to 1000 kg N km^{-2} or 50 kg P km^{-2}) of nitrogen (N) and phosphorus (P) (Xie and Ringler 2017).

Overlapping land-based challenges affect all land-use categories: croplands, rangelands, semi-natural forests, villages, dense settlements, wild forests and sparse trees and barren lands. These land-use categories can be defined as anthropogenic biomes, or anthromes, and their global distribution was mapped by Ellis and Ramankutty (2008) (Figure 6.2).

The majority of the global population is concentrated in dense settlements and villages, accounting for less than 7% of the global ice-free land area, while croplands and rangelands use 39% of land. The remainder of the ice-free land area (more than half) is used by semi-natural forests, by wild forests, sparse trees and barren lands (Table 6.1).

Land-use types (or anthromes) are exposed to multiple overlapping challenges. Climate change could induce rapid warming in all land areas (Chapter 2). In close to 70% of the ice-free land area, the climate change adaptation challenge could be reinforced by a strong dissimilarity between end-of-century and current temperature and precipitation seasonal cycles (Netzel and Stepinski 2018). Chronic undernourishment (a component of food insecurity) is concentrated in 20% of global ice-free land area. Severe soil erosion (a proxy of land degradation) and desertification from land use affect 13% and 3% of ice-free land area, respectively. Both groundwater stress and severe water-quality decline (12% and 10% of ice-free land area, respectively) contribute to the water challenge. Threatened biodiversity hot-spots (15% of ice-free land area) are significant for the biodiversity challenge (Table 6.1).

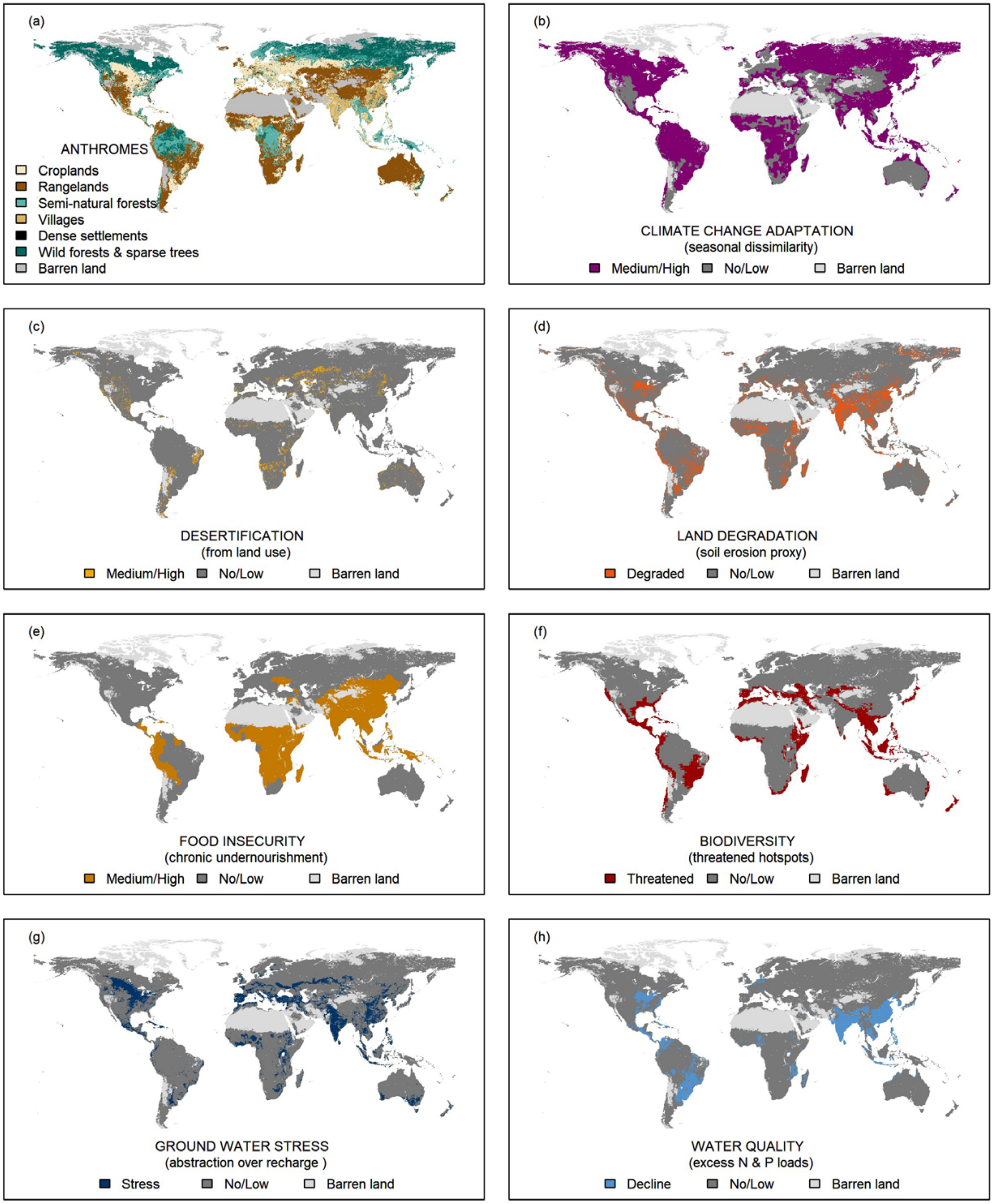

Figure 6.2 | Global distributions of land-use types and individual land-based challenges. (a) Land-use types (or anthromes, after Ellis and Ramankutty 2008); **(b)** Climate change adaptation challenge (estimated from the dissimilarity between current and end-of-century climate scenarios, Netzel and Stepinski 2018); **(c)** Desertification challenge (after Chapter 3, Figure 3.7c); **(d)** Land degradation challenge (estimated from a soil erosion proxy, one indicator of land degradation; Borrelli et al. 2017); **(e)** Food security challenge (estimated from chronic undernourishment, a component of food security, FAO 2017a); **(f)** biodiversity challenge (estimated from threatened biodiversity hotspots, a component of biodiversity, Mittermeier et al. 2011); **(g)** Groundwater stress challenge (estimated from water over-abstraction, Gassert et al. 2014); **(h)** Water quality challenge (estimated from critical nitrogen and phosphorus loads of water systems, Xie and Ringler 2017).

6

Table 6.1 | Global area of land-use types (or anthromes) and current percentage area exposure to individual (overlapping) land-based challenges. See Figure 6.2 and text for further details on criteria for individual challenges.

Land-use type (anthrome[a])	Anthrome area	Climate change adaptation (dissimilarity index proxy)[b]	Land degradation (soil erosion proxy)[c]	Desertification (ascribed to land use)[d]	Food security (chronic undernourishment)[e]	Biodiversity (threatened hotspot)[f]	Groundwater stress (over abstraction)[g]	Water quality (critical N-P loads)[h]
	% of ice-free land area[i]		% anthrome area exposed to an individual challenge					
Dense settlement	1	76	20	3	30	32	–	30
Village	5	70	49	3	78	28	77	59
Cropland	13	68	21	7	28	27	65	20
Rangeland	26	46	14	7	43	21	–	10
Semi-natural forests	14	91	17	0.7	–	21	–	7
Wild forests and sparse trees	17	98	4	0.5	–	2	–	0.3
Barren	19	53	6	0.9	2	4	–	0.4
*Organic soils	4	95	10	2	9	13	–	6
*Coastal wetlands	0.6	74	11	2	24	33	–	26
All anthromes	**100**	**69**	**13**	**3.2**	**20**	**15**	**12**	**10**

[a] Ellis and Ramankutty (2008); [b] Borrelli et al. 2017; [c] Netzel and Stepinski 2018; [d] from Figure 3.7c in Chapter 3; [e] FAO 2017a; [f] Mittermeier et al. 2011; [g] Gassert et al. 2014; [h] Xie and Ringler 2017; [i] the global ice-free land area is estimated at 134 Mkm^2.

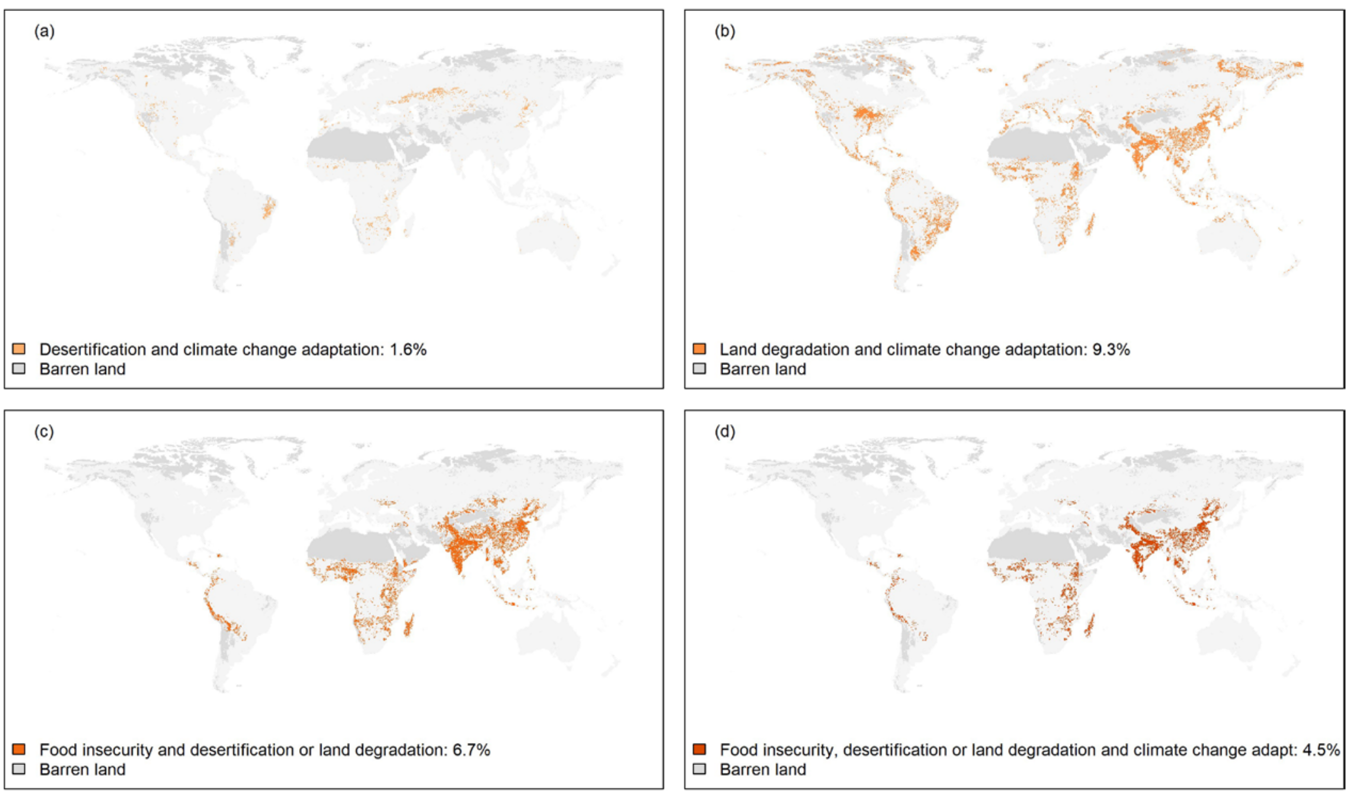

Figure 6.3 | Example of overlap between land challenges. (a) Overlap between the desertification (from land use) challenge and the climate change adaptation (strong dissimilarity in seasonal cycles) challenge. **(b)** Overlap between the land degradation (soil erosion proxy) challenge and the climate change adaptation challenge. **(c)** Overlap between the desertification or land degradation challenges and the food insecurity (chronic undernourishment) challenge. **(d)** Overlap between challenges shown in C and the climate change adaptation challenge. For challenges definitions, see text; references as in Figure 6.2.

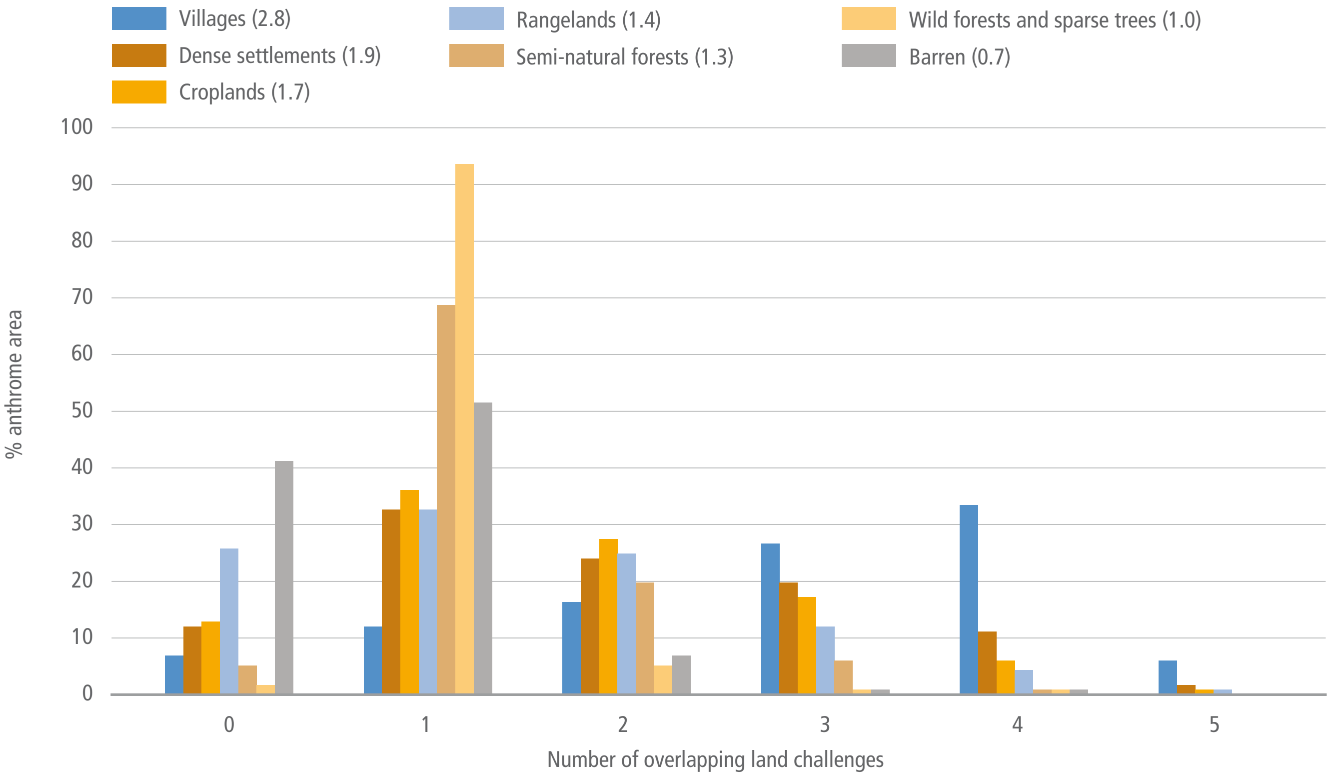

Figure 6.4 | Percentage distribution of land-use type (or anthrome) area by number of overlapping land challenges for the villages, dense settlements, croplands, rangelands, semi-natural forests, wild forests and sparse trees and barren land-use types. Values in brackets show the mean number of land challenges per land-use type. Land challenges include desertification (from land use), land degradation (soil erosion proxy), climate change adaptation (seasonal dissimilarity proxy), food security (chronic undernourishment), biodiversity (threatened hot spots), groundwater stress (over abstraction) and water quality (critical nitrogen and phosphorus loads).

Since land-based challenges overlap, part of the ice-free land area is exposed to combinations of two or more challenges. For instance, land degradation (severe soil erosion) or desertification from land use and food insecurity (chronic undernourishment) are combined with a strong climate change adaptation challenge (dissimilarity in seasonal cycles) in 4.5% of the ice-free land area (Figure 6.3).

The global distribution of land area by the number of overlapping land challenges (Figure 6.4) shows: the least exposure to land challenges in barren lands; less frequent exposure to two or more challenges in wild forests than in semi-natural forests; more frequent exposure to two or more challenges in agricultural anthromes (croplands and rangelands) and dense settlements than in forests; most frequent exposure to three or more challenges in villages compared to other land-use types. Therefore, land-use types intensively used by humans are, on average, exposed to a larger number of challenges than land-use types (or anthromes) least exposed to human use.

Case studies located in different world regions are presented for each anthrome, in order to provide historical context on the interlinkages between multiple challenges and responses (Box 6.1). Taken together, these case studies illustrate the large contrast across anthromes in land-based interventions, and show the way these interventions respond to combinations of challenges.

Box 6.1 | Case studies by anthrome type showing historical interlinkages between land-based challenges and the development of local responses

A. Croplands. Land degradation, groundwater stress and food insecurity: Soil and water conservation measures in the Tigray region of Ethiopia

In northern Ethiopia, the Tigray Region is a drought-prone area that has been subjected to severe land degradation (Frankl et al. 2013) and to recurrent drought and famine during 1888–1892, 1973–1974 and 1984–1985 (Gebremeskel et al. 2018). The prevalence of stunting and being underweight among children under five years is high (Busse et al. 2017) and the region was again exposed to a severe drought during the strong El Niño event of 2015–2016. Croplands are the dominant land-use type, with approximately 90% of the households relying on small-scale plough-based cultivation. Gullies affect nearly all slopes and frequently exceed 2 m in depth and 5 m in top width. Landsat imagery shows that cropland area peaked in 1984–1986, and increased erosion rates in the 1980s and 1990s caused the drainage density and volume to peak in 1994 (Frankl et al. 2013). Since around 2000, the large-scale implementation of soil and water conservation (SWC) measures, integrated catchment management,

6

Box 6.1 (continued)

conservation agriculture and indigenous tree regeneration has started to yield positive effects on the vegetation cover and led to the stabilisation of about 25% of the gullies by 2010 (Frankl et al. 2013). Since 1991, farmers have provided labour for SWC in January as a free service for 20 consecutive working days, followed by food for work for the remaining days of the dry season. Most of the degraded landscapes have been restored, with positive impacts over the last two decades on soil fertility, water availability and crop productivity. However, misuse of fertilisers, low survival of tree seedlings and lack of income from exclosures may affect the sustainability of these land restoration measures (Gebremeskel et al. 2018).

B. Rangelands. Biodiversity hotspot, land degradation and climate change: Pasture intensification in the Cerrados of Brazil

Cerrados are a tropical savannah ecoregion in Brazil corresponding to a biodiversity hot spot with less than 2% of its region protected in national parks and conservation areas (Cava et al. 2018). Extensive cattle ranching (limited mechanisation, low use of fertiliser and seed inputs) has led to pasture expansion, including clearing forests to secure properties rights, occurring mainly over 1950–1975 (Martha et al. 2012). Despite observed productivity gains made over the last three decades (Martha et al. 2012), more than half of the pasture area is degraded to some extent, and challenges remain to reverse grassland degradation while accommodating growing demand and simultaneously avoiding the conversion of natural habitats (de Oliveira Silva et al. 2018). The largest share of production is on unfertilised pastures, often sown with perennial forage grasses of African origin, mainly *Brachiaria spp.* (Cardoso et al. 2016). This initial intensification era was partly at the expense of significant uncontrolled deforestation, and average animal stocking rates remained well below the potential carrying capacity (Strassburg et al. 2014). Changes in land use are difficult to reverse since pasture abandonment does not lead to the spontaneous restoration of old-growth savannah (Cava et al. 2018); moreover, pasture to crop conversion is frequent, supporting close to half of cropland expansion in Mato Grosso state over 2000–2013 (Cohn et al. 2016). Pasture intensification through liming, fertilisation and controlled grazing could increase soil organic carbon and reduce net GHG emission intensity per unit meat product, but only at increased investment cost per unit of area (de Oliveira Silva et al. 2017). Scenarios projecting a decoupling between deforestation and increased pasture intensification, provide the basis for a Nationally Determined Contribution (NDC) of Brazil that is potentially consistent with accommodating an upward trend in livestock production to meet increasing demand (de Oliveira Silva et al. 2018). Deforestation in Brazil has declined significantly between 2004 and 2014 in the national inventory, but recent data and analyses suggest that the decrease in deforestation and the resulting GHG emissions reductions have slowed down or even stopped (UNEP 2017).

C. Semi-natural forests. Biodiversity hotspot, land degradation, climate change and food insecurity: Restoration and resilience of tropical forests in Indonesia

During the last two decades, forest cover in Indonesia declined by 150,000 km^2 in the period 1990–2000 (Stibig et al. 2014) and approximately 158,000 km^2 in the period 2000–2012 (Hansen et al. 2013), most of which was converted to agricultural lands (e.g., oil palm, pulpwood plantations). According to recent estimates, deforestation in Indonesia mainly concerns primary forests, including intact and degraded forests, thus leading to biodiversity loss and reduced carbon sequestration potentials (e.g., Margono et al. 2014). For example, Graham et al. (2017) estimated that the following strategies to reduce deforestation and forest degradation may cost-effectively increase carbon sequestration and reduce carbon emissions in 30 years: reforestation (3.54 $GtCO_2$), limiting the expansion of oil palm and timber plantations into forest (3.07 $GtCO_2$ and 3.05 $GtCO_2$, respectively), reducing illegal logging (2.34 $GtCO_2$), and halting illegal forest loss in protected areas (1.52 $GtCO_2$) at a total cost of 15.7 USD tC^{-1}. The importance of forest mitigation in Indonesia is indicated by the NDC, where between half and two-thirds of the 2030 emission target relative to a business-as-usual scenario is from reducing deforestation, forest degradation, peatland drainage and fires (Grassi et al. 2017). Avoiding deforestation and reforestation could have multiple co-benefits by improving biodiversity conservation and employment opportunities, while reducing illegal logging in protected areas. However, these options could also have adverse side effects if they deprive local communities of access to natural resources (Graham et al. 2017). The adoption of the Roundtable on Sustainable Palm Oil certification in oil palm plantations reduced deforestation rates by approximately 33% in the period 2001–2015 (co-benefits with mitigation), and fire rates much more than for non-certified plantations (Carlson et al. 2018). However, given that large-scale oil palm plantations are one of the largest drivers of deforestation in Indonesia, objective information on the baseline trajectory for land clearance for oil palm is needed to further assess commitments, regulations and transparency in plantation development (Gaveau et al. 2016). For adaptation options, the community forestry scheme *Hutan Desa* (Village Forest) in Sumatra and Kalimantan helped to avoid deforestation (co-benefits with mitigation) by between 0.6 and 0.9 ha km^{-2} in Sumatra and 0.6 and 0.8 ha km^{-2} in Kalimantan in the period 2012–2016; Santika et al. 2017), improve local livelihood options, and restore degraded ecosystems (positive side effects for NCP provision) (e.g., Pohnan et al. 2015). Finally, the establishment of Ecosystem Restoration Concessions in Indonesia (covering more than 5,500 km^2 of forests now, and 16,000 km^2 allocated for the future) facilitates the planting of commercial timber species (co-benefits with mitigation), while assisting natural regeneration, preserving important habitats and species, and improving local well-being and incomes (positive side effects for Nature's Contributions to People provision), at relatively lower costs compared with timber concessions (Silalahi et al. 2017).

Box 6.1 (continued)

D. Villages. Land degradation, groundwater overuse, climate change and food insecurity: Climate smart villages in India

Indian agriculture, which includes both monsoon-dependent rainfed (58%) and irrigated agriculture, is exposed to climate variability and change. Over the past years, the frequency of droughts, cyclones, and hailstorms has increased, with severe droughts in eight of 15 years between 2002 and 2017 (Srinivasa Rao et al. 2016; Mujumdar et al. 2017). Such droughts result in large yield declines for major crops like wheat in the Indo-Gangetic Plain (Zhang et al. 2017). The development of a submersible pump technology in the 1990s, combined with public policies that provide farmers with free electricity for groundwater irrigation, resulted in a dramatic increase in irrigated agriculture (Shah et al. 2012). This shift has led to increased dependence on irrigation from groundwater and induced a groundwater crisis, with large impacts on socio-ecosystems. An increasing number of farmers report bore-well failures, either due to excessive pumping of an existing well or a lack of water in new wells. The decrease in the groundwater table level has suppressed the recharge of river beds, turning permanent rivers into ephemeral streams (Srinivasan et al. 2015). Wells have recently been drilled in upland areas, where groundwater irrigation is also increasing (Robert et al. 2017). Additional challenges include declining soil organic matter and fertility under monocultures and rice/wheat systems. Unoccupied land is scarce, meaning that the potential for expanding the area farmed is very limited (Aggarwal et al. 2018). In rural areas, diets are deficient in protein, dietary fibre and iron, and mainly comprised of cereals and pulses grown and/or procured through welfare programmes (Vatsala et al. 2017). Cultivators are often indebted, and suicide rates are much higher than the national average, especially for those strongly indebted (Merriott 2016). Widespread use of diesel pumps for irrigation, especially for paddies, high use of inorganic fertilisers and crop residue burning lead to high GHG emissions (Aggarwal et al. 2018). The Climate-Smart Village (CSV) approach aims at increasing farm yield, income, input use efficiency (water, nutrients, and energy) and reducing GHG emissions (Aggarwal et al. 2018). Climate-smart agriculture interventions are considered in a broad sense by including practices, technologies, climate information services, insurance, institutions, policies, and finance. Options differ based on the CSV site, its agro-ecological characteristics, level of development, and the capacity and interest of farmers and the local government (Aggarwal et al. 2018). Selected interventions included crop diversification, conservation agriculture (minimum tillage, residue retention, laser levelling), improved varieties, weather-based insurance, agro-advisory services, precision agriculture and agroforestry. Farmers' cooperatives were established to hire farm machinery, secure government credit for inputs, and share experiences and knowledge. Tillage practices and residue incorporation increased rice–wheat yields by 5–37%, increased income by 28–40%, reduced GHG emissions by 16–25%, and increased water-use efficiency by 30% (Jat et al. 2015). The resulting portfolio of options proposed by the CSV approach has been integrated with the agricultural development strategy of some states like Haryana.

E. Dense settlements. Climate change and food: Green infrastructures

Extreme heat events have led to particularly high rates of mortality and morbidity in cities, as urban populations are pushed beyond their adaptive capacities, leading to an increase in mortality rates of 30–130% in major cities in developed countries (Norton et al. 2015). Increased mortality and morbidity from extreme heat events are exacerbated in urban populations by the urban heat island effect (Gabriel and Endlicher 2011; Schatz and Kucharik 2015), which can be limited by developing green infrastructure in cities. Urban green infrastructure includes public and private green spaces – such as remnant native vegetation, parks, private gardens, golf courses, street trees, urban farming – and more engineered options, such as green roofs, green walls, biofilters and raingardens (Norton et al. 2015). Increasing the amount of vegetation, or green infrastructure, in a city is one way to help reduce urban air temperature maxima and variation. Increasing vegetation by 10% in Melbourne, Australia was estimated to reduce daytime urban surface temperatures by approximately 1°C during extreme heat events (Coutts and Harris 2013). Urban farming (a type of urban green infrastructure) is largely driven by the desire to reconnect food production and consumption (Whittinghill and Rowe 2012) (Chapter 5). Even though urban farming can only meet a very small share of the overall urban food demand, it provides fresh and local food, especially perishable fruits and crops that are usually shipped from far and sold at high prices (Thomaier et al. 2015). Food-producing urban gardens and farms are often started by grassroots initiatives (Ercilla-Montserrat et al. 2019) that occupy vacant urban spaces. In recent years, a growing number of urban farming projects (termed Zero-Acreage farming, or Z-farming, Thomaier et al. 2015) were established in and on existing buildings, using rooftop spaces or abandoned buildings through contracts between food businesses and building owners. Almost all Z-farms are located in cities with more than 150,000 inhabitants, with a majority in North American cities such as New York City, Chicago and Toronto (Thomaier et al. 2015). They depend on the availability of vacant buildings and roof tops, thereby competing with other uses, such as roof-based solar systems. Urban farming, however, has potentially high levels of soil pollution and air pollutants, which may lead to crop contamination and health risks. These adverse effects could be reduced on rooftops (Harada et al. 2019) or in controlled environments.

6.1.4 Challenges represented in future scenarios

In this section, the evolution of several challenges (climate change, mitigation, adaptation, desertification, land degradation, food insecurity, biodiversity and water) in the future are assessed, focusing on global analyses. The effect of response options on these land challenges in the future is discussed in Section 6.4.4. Where possible, studies quantifying these challenges in the Shared Socio-economic Pathways (SSPs) (O'Neill et al. 2014) (Chapter 1, Cross-Chapter Box 1, and Cross-Chapter Box 9 in this chapter), should be used to assess which future scenarios could experience multiple challenges in the future.

Climate change: Without any additional efforts to mitigate, global mean temperature rise is expected to increase by anywhere from 2°C to 7.8°C in 2100 relative to the 1850–1900 reference period (Clarke et al. 2014; Chapter 2). The level of warming varies, depending on the climate model (Collins et al. 2013), uncertainties in the Earth system (Clarke et al. 2014), and socio-economic/technological assumptions (Clarke et al. 2014; Riahi et al. 2017). Warming over land is 1.2 to 1.4 times higher than global mean temperature rise; warming in the Arctic region is 2.4 to 2.6 times higher than warming in the tropics (Collins et al. 2013). Increases in global mean temperature are accompanied by increases in global precipitation; however, the effect varies across regions, with some regions projected to see increases in precipitation and others to see decreases (Collins et al. 2013) (Chapter 2). Additionally, climate change also has implications for extreme events (e.g., drought, heat waves, etc.), freshwater availability, and other aspects of the terrestrial system (Chapter 2).

Mitigation: Challenges to mitigation depend on the underlying emissions and 'mitigative capacity', including technology availability, policy institutions, and financial resources (O'Neill et al. 2014). Challenges to mitigation are high in SSP3 and SSP5, medium in SSP2, and low in SSP1 and SSP4 (O'Neill et al. 2014, 2017; Riahi et al. 2017).

Adaptation: Challenges to adaptation depend on climate risk and adaptive capacity, including technology availability, effectiveness of institutions, and financial resources (O'Neill et al. 2014). Challenges to adaptation are high in SSP3 and SSP4, medium in SSP2, and low in SSP1 and SSP5 (O'Neill et al. 2014, 2017; Riahi et al. 2017).

Desertification: The combination of climate and land-use changes can lead to decreases in soil cover in drylands (Chapter 3). Population living in drylands is expected to increase by 43% in the SSP2-Baseline, due to both population increases and an expansion of dryland area (UNCCD 2017).

Land degradation: Future changes in land use and climate have implications for land degradation, including impacts on soil erosion, vegetation, fire, and coastal erosion (Chapter 4; IPBES 2018). For example, soil organic carbon is expected to decline by 99 $GtCO_2e$ in 2050 in an SSP2-Baseline scenario, due to both land management and expansion in agricultural area (Ten Brink et al. 2018).

Food insecurity: Food insecurity in future scenarios varies significantly, depending on socio-economic development and study. For example, the population at risk of hunger ranges from 0 to 800 million in 2050 (Hasegawa et al. 2015a; Ringler et al. 2016; Fujimori et al. 2018; Hasegawa et al. 2018; Fujimori et al. 2019; Baldos and Hertel 2015) and 0–600 million in 2100 (Hasegawa et al. 2015a). Food prices in 2100 in non-mitigation scenarios range from 0.9 to about two times their 2005 values (Hasegawa et al. 2015a; Calvin et al. 2014; Popp et al. 2017). Food insecurity depends on both income and food prices (Fujimori et al. 2018). Higher income (e.g., SSP1, SSP5), higher yields (e.g., SSP1, SSP5), and less meat intensive diets (e.g., SSP1) tend to result in reduced food insecurity (Hasegawa et al. 2018; Fujimori et al. 2018).

Biodiversity: Future species extinction rates vary from modest declines to 100-fold increases from 20th century rates, depending on the species (e.g., plants, vertebrates, invertebrates, birds, fish, corals), the degree of land-use change, the level of climate change, and assumptions about migration (Pereira et al. 2010). Mean species abundance (MSA) is also estimated to decline in the future by 10–20% in 2050 (Van Vuuren et al. 2015; Pereira et al. 2010). Scenarios with greater cropland expansion lead to larger declines in MSA (UNCCD 2017) and species richness (Newbold et al. 2015).

Water stress: Changes in water supply (due to climate change) and water demand (due to socio-economic development) in the future have implications for water stress. Water withdrawals for irrigation increase from about 2500 $km^3 yr^{-1}$ in 2005 to between 2900 and 9000 $km^3 yr^{-1}$ at the end of the century (Chaturvedi et al. 2013; Wada and Bierkens 2014; Hejazi et al. 2014a; Kim et al. 2016; Graham et al. 2018; Bonsch et al. 2015); total water withdrawals at the end of the century range from 5000 to 13,000 $km^3 yr^{-1}$ (Wada and Bierkens 2014; Hejazi et al. 2014a; Kim et al. 2016; Graham et al. 2018). The magnitude of change in both irrigation and total water withdrawals depend on population, income, and technology (Hejazi et al. 2014a; Graham et al. 2018). The combined effect of changes in water supply and water demand will lead to an increase of between 1 billion and 6 billion people living in water-stressed areas (Schlosser et al. 2014; Hanasaki et al. 2013; Hejazi et al. 2014b). Changes in water quality are not assessed here but could be important (Liu et al. 2017).

Scenarios with multiple challenges: Table 6.2 summarises the challenges across the five SSP Baseline scenarios.

Table 6.2 | Assessment of future challenges to climate change, mitigation, adaptation, desertification, land degradation, food insecurity, water stress, and biodiversity in the SSP Baseline scenarios.

SSP	Summary of challenges
SSP1	SSP1 (Van Vuuren et al. 2017b) has low challenges to mitigation and adaptation. The resulting Baseline scenario includes: – continued, but moderate, *climate change*: global mean temperature increases by 3 to 3.5°C in 2100 (Huppmann et al. 2018; Riahi et al. 2017) – low levels of *food insecurity*: malnourishment is eliminated by 2050 (Hasegawa et al. 2015a) – declines in *biodiversity*: biodiversity loss increases from 34% in 2010 to 38% in 2100 (UNCCD 2017) – high *water stress*: global water withdrawals decline slightly from the baseline in 2071–2100, but about 2.6 billion people live in water stressed areas (Hanasaki et al. 2013). Additionally, this scenario is likely to have lower challenges related to desertification, land degradation, and biodiversity loss than SSP2 as it has lower population, lower land-use change and lower climate change (Riahi et al. 2017).
SSP2	SSP2 (Fricko et al. 2017) is a scenario with medium challenges to mitigation and medium challenges to adaptation. The resulting Baseline scenario includes: – continued *climate change*: global mean temperature increases by 3.8°C to 4.3°C in 2100 (Fricko et al. 2017; Huppmann et al. 2018; Riahi et al. 2017) – increased challenges related to *desertification*: the population living in drylands is expected to increase by 43% in 2050 (UNCCD 2017) – increased *land degradation*: soil organic carbon is expected to decline by 99 $GtCO_2e$ in 2050 (Ten Brink et al. 2018) – low levels of *food insecurity*: malnourishment is eliminated by 2100 (Hasegawa et al. 2015a) – declines in *biodiversity*: biodiversity loss increases from 34% in 2010 to 43% in 2100 (UNCCD 2017) – high *water stress*: global water withdrawals nearly doubles from the baseline in 2071–2100, with about 4 billion people living in water stressed areas (Hanasaki et al. 2013).
SSP3	SSP3 (Fujimori et al. 2017) is a scenario with high challenges to mitigation and high challenges to adaptation. The resulting Baseline scenario includes: – continued *climate change*: global mean temperature increases by 4°C to 4.8°C in 2100 (Huppmann et al. 2018; Riahi et al. 2017) – high levels of *food insecurity*: about 600 million malnourished in 2100 (Hasegawa et al. 2015a) – declines in *biodiversity*: biodiversity loss increases from 34% in 2010 to 46% in 2100 (UNCCD 2017) – high *water stress*: global water withdrawals more than double from the baseline in 2071–2100, with about 5.5 billion people living in water stressed areas (Hanasaki et al. 2013). Additionally, this scenario is likely to have higher challenges to desertification, land degradation, and biodiversity loss than SSP2 as it has higher population, higher land-use change and higher climate change (Riahi et al. 2017).
SSP4	SSP4 (Calvin et al. 2017) has high challenges to adaptation but low challenges to mitigation. The resulting Baseline scenario includes: – continued *climate change*: global mean temperature increases by 3.4°C to 3.8°C in 2100 (Calvin et al. 2017; Huppmann et al. 2018; Riahi et al. 2017) – high levels of *food insecurity*: about 400 million malnourished in 2100 (Hasegawa et al. 2015a) – high *water stress*: about 3.5 billion people live in water stressed areas in 2100 (Hanasaki et al. 2013). Additionally, this scenario is likely to have similar effects on biodiversity loss as SSP2 as it has similar land-use change and similar climate change (Riahi et al. 2017).
SSP5	SSP5 (Kriegler et al. 2017) has high challenges to mitigation but low challenges to adaptation. The resulting Baseline scenario includes: – continued *climate change*: global mean temperature increases by 4.6°C to 5.4°C in 2100 (Kriegler et al. 2017; Huppmann et al. 2018; Riahi et al. 2017) – low levels of *food insecurity*: malnourishment is eliminated by 2050 (Hasegawa et al. 2015a) – increased water use and water scarcity: global water withdrawals increase by about 80% in 2071–2100, with nearly 50% of the population living in water stressed areas (Hanasaki et al. 2013). Additionally, this scenario is likely to have higher effects on biodiversity loss as SSP2 as it has similar land-use change and higher climate change (Riahi et al. 2017).

6.2 Response options, co-benefits and adverse side effects across the land challenges

This section describes the integrated response options available to address the land challenges of climate change mitigation, climate change adaptation, desertification, land degradation and food security. These can be categorised into options that rely on (i) land management, (ii) value chain management, and (iii) risk management (Figure 6.5). The land management integrated response options can be grouped according to those that are applied in agriculture, in forests, on soils, in other/all ecosystems and those that are applied specifically for carbon dioxide removal (CDR). The value chain management integrated response options can be categorised as those based demand management and supply management. The risk management options are grouped together (Figure 6.5).

Note that the integrated response options are not mutually exclusive – for example, cropland management might also increase soil organic matter stocks – and a number of the integrated response options are comprised of a number of practices – for example, improved cropland management is a collection of practices consisting of:

1. management of the crop, including high-input carbon practices, for example, improved crop varieties, crop rotation, use of cover crops, perennial cropping systems, agricultural biotechnology
2. nutrient management: including optimised fertiliser application rate, fertiliser type [organic and mineral], timing, precision application, inhibitors
3. reduced tillage intensity and residue retention
4. improved water management: including drainage of waterlogged mineral soils and irrigation of crops in arid/semi-arid conditions
5. improved rice management, including water management such as mid-season drainage and improved fertilisation and residue management in paddy rice systems.

In this section, we deal only with integrated response options, not the policies that are currently or could be implemented to enable their application; that is the subject of Chapter 7. Also note that enabling conditions such as indigenous and local knowledge, gender issues, governance and so on are not categorised as integrated response options (Section 6.1.2). Some suggested methods to address land challenges are better described as *overarching frameworks* than as integrated response options. For example, *climate smart agriculture* is a collection of integrated

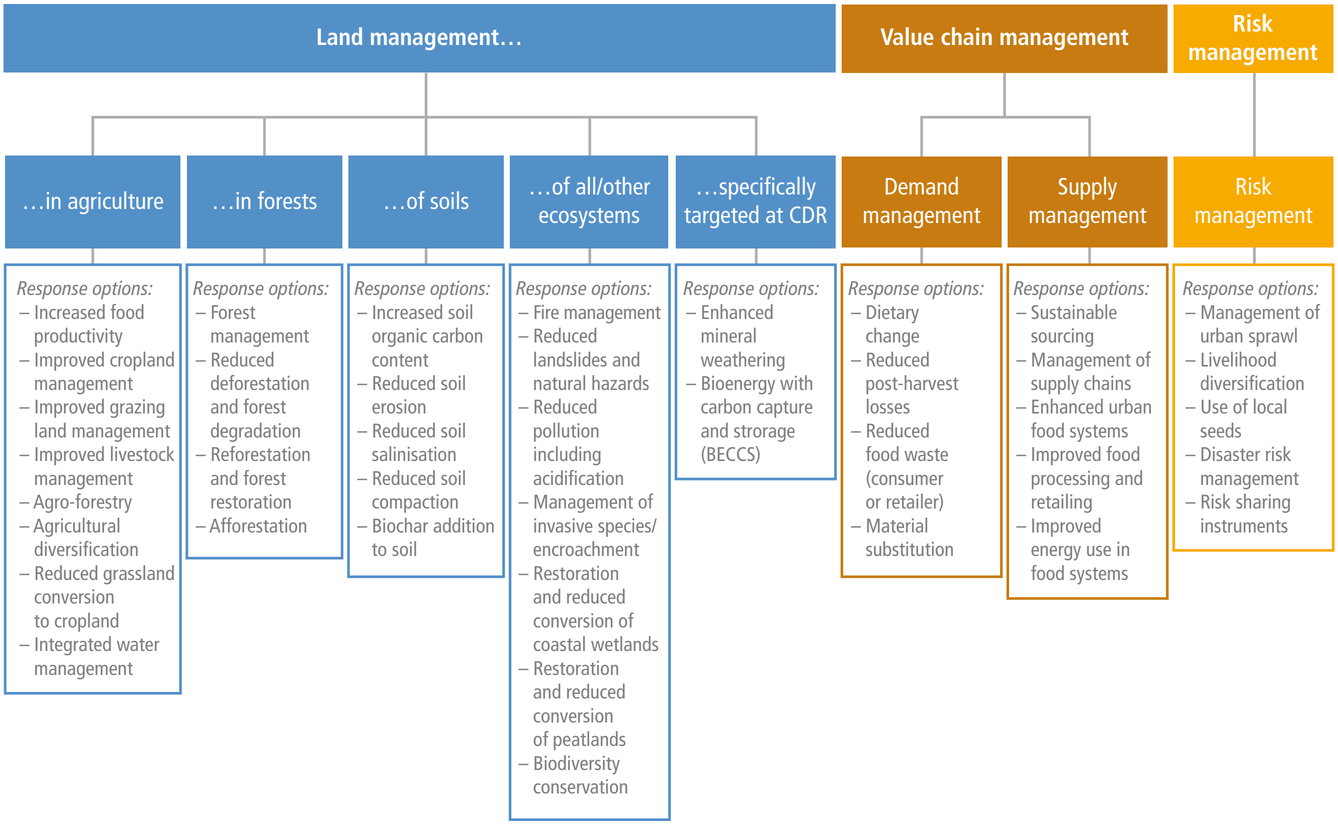

Figure 6.5 | Broad categorisation of response options categorised into three main classes and eight sub-classes.

response options aimed at delivering mitigation and adaptation in agriculture, including improved cropland management, grazing land management and livestock management. Table 6.3 shows how a number of overarching frameworks are comprised of a range of integrated response options.

Similarly, policy goals, such as *land degradation neutrality* (discussed further in Chapter 7), are not considered as integrated response options. For this reason, *land degradation neutrality*, and overarching frameworks, such as those described in Table 6.3 do not appear as response options in the following sections, but the component integrated response options that contribute to these policy goals or overarching frameworks are addressed in detail.

Table 6.3 | Examples of overarching frameworks that consist of a range of response options.

Framework (definition used)	Nature-based solutions (IUCN)	Agro-ecology (FAO)	Climate smart agriculture (FAO)	Ecosystem-based adaptation (CBD)	Conservation agriculture (FAO)	Community-based adaptation (IIED)	Integrated landscape management including integrated coastal zone management (FAO)	Precision agriculture (FAO)	Sustainable forest management (UN)	Sustainable intensification (Cross-Chapter Box 5 in Chapter 5)	Organic agriculture (FAO)
Response options based on land management											
Increased food productivity			●		●		●	●		●	
Improved cropland management		●	●		●	●	●	●		●	●
Improved grazing land management		●	●	●		●	●			●	●
Improved livestock management		●	●			●	●			●	●

Framework (definition used)	Nature-based solutions (IUCN)	Agro-ecology (FAO)	Climate smart agriculture (FAO)	Ecosystem-based adaptation (CBD)	Conservation agriculture (FAO)	Community-based adaptation (IIED)	Integrated landscape management including integrated coastal zone management (FAO)	Precision agriculture (FAO)	Sustainable forest management (UN)	Sustainable intensification (Cross-Chapter Box 5 in Chapter 5)	Organic agriculture (FAO)
Agroforestry		●	●	●		●	●			●	●
Agricultural diversification		●	●				●			●	●
Reduced grassland conversion to cropland		●		●		●	●				
Integrated water management	●	●	●	●	●	●	●	●		●	●
Forest management	●			●		●	●		●		
Reduced deforestation and forest degradation		●		●		●	●				
Reforestation and forest restoration	●	●		●		●	●		●		
Afforestation				●		●	●				
Increased soil organic carbon content		●	●	●	●		●			●	●
Reduced soil erosion		●	●	●	●		●			●	●
Reduced soil salinisation		●	●	●	●		●	●		●	●
Reduced soil compaction		●	●	●	●		●			●	●
Biochar addition to soil		●	●								
Fire management		●	●	●		●	●		●		
Reduced landslides and natural hazards		●	●	●		●	●				
Reduced pollution including acidification							●	●		●	●
Management of invasive species/encroachment	●	●		●		●	●		●		●
Restoration and reduced conversion of coastal wetlands		●		●		●	●				
Restoration and reduced conversion of peatlands		●	●	●		●	●				
Biodiversity conservation	●	●	●	●	●	●	●		●	●	
Enhanced weathering of minerals											
Bioenergy and BECCS							●				
Response options based on value chain management											
Dietary change		●									●
Reduced post-harvest losses		●	●			●		●			●
Reduced food waste (consumer or retailer)		●									
Material substitution											
Sustainable sourcing		●	●			●	●				●
Management of supply chains		●	●								
Enhanced urban food systems		●	●			●	●	●		●	●
Improved food processing and retailing		●									
Improved energy use in food systems		●	●		●			●		●	
Response options based on risk management											
Management of urban sprawl				●		●	●				
Livelihood diversification		●	●	●		●	●	●			
Use of local seeds	●	●	●	●		●	●				
Disaster risk management	●			●		●	●				●
Risk sharing instruments										●	

Table 6.4 | Mapping of response options considered in this report (SRCCL) and SR15.

SRCCL Response option/options	SR15 Response option/options
Afforestation	Afforestation
Reforestation and forest restoration	Reforestation and reduced land degradation and forest restoration
Agricultural diversification	Mixed crop-livestock systems
Agroforestry	Agroforestry and silviculture
Biochar addition to soil	Biochar
Biodiversity conservation	Biodiversity conservation
Bioenergy and bioenergy with carbon capture and storage (BECCS)	BECCS (through combustion, gasification, or fermentation)
Dietary change	Dietary changes, reducing meat consumption
Disaster risk management	Climate services
	Community-based adaptation
Enhanced urban food systems	Urban and peri-urban agriculture and forestry
Enhanced weathering of minerals	Mineralisation of atmospheric carbon dioxide (CO_2) through enhanced weathering of rocks
Fire management	Fire management and (ecological) pest control
Forest management	Forest management
Improved cropland management	Methane reductions in rice paddies
Improved cropland management	Nitrogen pollution reductions, e.g., by fertiliser reduction, increasing nitrogen fertiliser efficiency, sustainable fertilisers
	Precision agriculture
	Conservation agriculture
Improved food processing and retailing	
Improved grazing land management	Livestock and grazing management, e.g., methane and ammonia reductions in ruminants through feeding management or feed additives, or manure management for local biogas production to replace traditional biomass use
Improved livestock management	
	Manure management
Increased energy efficiency in food systems	
Increased food productivity	Increasing agricultural productivity
Increased soil organic carbon content	Changing agricultural practices enhancing soil carbon
	Soil carbon enhancement, enhancing carbon sequestration in biota and soils, e.g., with plants with high carbon sequestration potential – also agriculture, forestry and other land-use (AFOLU) measure.
Integrated water management	Irrigation efficiency
Livelihood diversification	
Management of invasive species/encroachment	
Management of supply chains	
Management of urban sprawl	Urban ecosystem services
	Climate resilient land use
Material substitution	Material substitution of fossil CO_2 with bio-CO_2 in industrial application (e.g., the beverage industry)
	Carbon capture and usage (CCU); bioplastics (bio-based materials replacing fossil fuel uses as feedstock in the production of chemicals and polymers), carbon fibre
Reduced soil erosion	
Reduced soil compaction	
Reduced deforestation	Reduced deforestation, forest protection, avoided forest conversion
Reduced food waste (consumer or retailer)	Reduction of food waste (incl. reuse of food processing waste for fodder)
Reduced grassland conversion to cropland	
Reduced landslides and natural hazards	
Reduced pollution including acidification	Reduced air pollution
Reduced post-harvest losses	
Reduced soil salinisation	
Restoration and reduced conversion of coastal wetlands	Managing coastal stress
	Restoration of wetlands (e.g., coastal and peat-land restoration, blue carbon) and wetlands management
Restoration and reduced conversion of peatlands	
Risk sharing instruments	Risk sharing
Sustainable sourcing	
Use of local seeds	

SR15 considered a range of response options (from a mitigation/adaptation perspective only). Table 6.4 shows how the SR15 options map on to the response options considered in this report (SRCCL). Note that this report excludes most of the energy-related options from SR15, as well as green infrastructure and sustainable aquaculture.

Before providing the quantitative assessment of the impacts of each response option in addressing mitigation, adaptation, desertification, land degradation and food security in Section 6.3, the integrated response options are descried in Section 6.2.1 and any context specificities in the effects are noted.

6.2.1 Integrated response options based on land management

6.2.1.1 Integrated response options based on land management in agriculture

Integrated response options based on land management in agriculture are described in Table 6.5, which also notes any context specificities, and provides the evidence base for the effects of the response options.

6.2.1.2 Integrated response options based on land management in forests

Integrated response options based on land management in forests are described in Table 6.6, which also notes any context specificities, and provides the evidence base for the effects of the response options.

6.2.1.3 Integrated response options based on land management of soils

Integrated response options based on land management of soils are described in Table 6.7, which also notes any context specificities, and provides the evidence base for the effects of the response options.

6.2.1.4 Integrated response options based on land management of all/other ecosystems

Integrated response options based on land management in all/other ecosystems are described in Table 6.8, which also notes any context specificities, and provides the evidence base for the effects of the response options.

6.2.1.5 Integrated response options based on land management specifically for carbon dioxide removal (CDR)

Integrated response options based on land management specifically for CDR are described in Table 6.9, which also notes any context specificities, and provides the evidence base for the effects of the response options.

Table 6.5 | Integrated response options based on land management in agriculture.

Integrated response option	Description	Context and caveats	Supporting evidence
Increased food productivity	Increased food productivity arises when the output of food commodities increases per unit of input, e.g., per unit of land or water. It can be realised through many other interventions such as improved cropland, grazing land and livestock management.	Many interventions to increase food production, particularly those predicated on very large inputs of agro-chemicals, have a wide range of negative externalities leading to the proposal of sustainable intensification as a mechanism to deliver future increases in productivity that avoid these adverse outcomes. Intensification through additional input of nitrogen fertiliser, for example, would result in negative impacts on climate, soil, water and air pollution. Similarly, if implemented in a way that over-exploits the land, significant negative impacts would occur, but if achieved through sustainable intensification, and used to spare land, it could reduce the pressure on land.	Cross-Chapter Box 6 in Chapter 5; Chapter 3 Balmford et al. 2018; Burney et al. 2010; Foley et al. 2011; Garnett et al. 2013; Godfray et al. 2010; IPBES 2018; Lal 2016; Lamb et al. 2016; Lobell et al. 2008; Shcherbak et al. 2014; Smith et al. 2013; Tilman et al. 2011
Improved cropland management	Improved cropland management is a collection of practices consisting of a) *management of the crop*: including high input carbon practices, for example, improved crop varieties, crop rotation, use of cover crops, perennial cropping systems, integrated production systems, crop diversification, agricultural biotechnology, b) *nutrient management*: including optimised fertiliser application rate, fertiliser type (organic manures, compost and mineral), timing, precision application, nitrification inhibitors, c) *reduced tillage intensity and residue retention*, d) *improved water management*: including drainage of waterlogged mineral soils and irrigation of crops in arid/semi-arid conditions, e) *improved rice management*: including water management such as mid-season drainage and improved fertilisation and residue management in paddy rice systems, and f) *biochar application*.	Improved cropland management can reduce GHG emissions and create soil carbon sinks, though if poorly implemented, it could increase nitrous oxide and methane emissions from nitrogen fertilisers, crop residues and organic amendments. It can improve resilience of food crop production systems to climate change, and can be used to tackle desertification and land degradation by improving sustainable land management. It can also contribute to food security by closing crop yield gaps to increase food productivity.	Chapter 4; Chapter 3; Chapter 2; Chapter 5 Bryan et al. 2009; Chen et al. 2010; Labrière et al. 2015; Lal 2011; Poeplau and Don 2015; Porter et al. 2014; Smith 2008b; Smith et al. 2014; Tilman et al. 2011

6

Integrated response option	Description	Context and caveats	Supporting evidence
Improved grazing land management	Improved grazing land management is a collection of practices consisting of a) *management of vegetation*: including improved grass varieties/sward composition, deep rooting grasses, increased productivity, and nutrient management, b) *animal management*: including appropriate stocking densities fit to carrying capacity, fodder banks, and fodder diversification, and c) *fire management*: improved use of fire for sustainable grassland management, including fire prevention and improved prescribed burning (see also fire management as a separate response option) (Table 6.8).	Improved grazing land management can increase soil carbon sinks, reduce GHG emissions, improve the resilience of grazing lands to future climate change, help reduce desertification and land degradation by optimising stocking density and reducing overgrazing, and can enhance food security through improved productivity.	Chapter 2; Chapter 3; Chapter 4; Chapter 5; Section 6.4 Archer et al. 2011; Briske et al. 2015; Conant et al. 2017; Herrero et al. 2016; Porter et al. 2014; Schwilch et al. 2014; Smith et al. 2014; Tighe et al. 2012
Improved livestock management	Improved livestock management is a collection of practices consisting of a) *improved feed and dietary additives* (e.g., bioactive compounds, fats), used to increase productivity and reduce emissions from enteric fermentation; b) *breeding* (e.g., breeds with higher productivity or reduced emissions from enteric fermentation), c) *herd management,* including decreasing neo-natal mortality, improving sanitary conditions, animal health and herd renewal, and diversifying animal species, d) *emerging technologies* (of which some are not legally authorised in several countries) such as propionate enhancers, nitrate and sulphate supplements, archaea inhibitors and archaeal vaccines, methanotrophs, acetogens, defaunation of the rumen, bacteriophages and probiotics, ionophores/antibiotics; and e) *improved manure management,* including manipulation of bedding and storage conditions, anaerobic digesters; biofilters, dietary change and additives, soil-applied and animal-fed nitrification inhibitors, urease inhibitors, fertiliser type, rate and timing, manipulation of manure application practices, and grazing management.	Improved livestock management can reduce GHG emissions, particularly from enteric methane and manure management. It can improve the resilience of livestock production systems to climate change by breeding better adapted livestock. It can help with desertification and land degradation, e.g., through use of more efficient and adapted breeds to allow reduced stocking densities. Improved livestock sector productivity can also increase food production.	Chapter 2; Chapter 3; Chapter 4; Chapter 5 Archer et al. 2011; Herrero et al. 2016; Miao et al. 2015; Porter et al. 2014; Rojas-Downing et al. 2017; Smith et al. 2008, 2014; Squires and Karami 2005; Tighe et al. 2012
Agroforestry	Agroforestry involves the deliberate planting of trees in croplands and silvo-pastoral systems.	Agroforestry sequesters carbon in vegetation and soils. The use of leguminous trees can enhance biological nitrogen fixation and resilience to climate change. Soil improvement and the provision of perennial vegetation can help to address desertification and land degradation. Agroforestry can increase agricultural productivity, with benefits for food security. Additionally, agroforestry can enable payments to farmers for ecosystem services and reduce vulnerability to climate shocks.	Antwi-Agyei et al. 2014; Benjamin et al. 2018; Guo et al. 2018; den Herder et al. 2017; Mbow et al. 2014a; Mosquera-Losada et al. 2018; Mutuo et al. 2005; Nair and Nair 2014; Ram et al. 2017; Rosenstock et al. 2014; Sain et al. 2017; Santiago-Freijanes et al. 2018; Sida et al. 2018; Vignola et al. 2015; Yirdaw et al. 2017
Agricultural diversification	Agricultural diversification includes a set of agricultural practices and products obtained in the field that aim to improve the resilience of farmers to climate variability and climate change and to economic risks posed by fluctuating market forces. In general, the agricultural system is shifted from one based on low-value agricultural commodities to one that is more diverse, composed of a basket of higher value-added products.	Agricultural diversification is targeted at adaptation but could also deliver a small carbon sink, depending on how it is implemented. It could reduce pressure on land, benefitting desertification, land degradation, food security and household income. However, the potential to achieve household food security is influenced by the market orientation of a household, livestock ownership, non-agricultural employment opportunities, and available land resources.	Birthal et al. 2015; Campbell et al. 2014; Cohn et al. 2017; Lambin and Meyfroidt 2011; Lipper et al. 2014; Massawe et al. 2016; Pellegrini and Tasciotti 2014; Waha et al. 2018
Reduced grassland conversion to cropland	Grasslands can be converted to croplands by ploughing of grassland and seeding with crops. Since croplands have a lower soil carbon content than grasslands and are also more prone to erosion than grasslands, reducing conversion of grassland to croplands will prevent soil carbon losses by oxidation and soil loss through erosion. These processes can be reduced if the rate of grassland conversion to cropland is reduced.	Stabilising soils by retaining grass cover also improves resilience, benefitting adaptation, desertification and land degradation. Since conversion of grassland to cropland usually occurs to remedy food security challenges, food security could be adversely affected, since more land is required to produce human food from livestock products on grassland than from crops on cropland.	Chapter 3; Chapter 4; Chapter 5 Clark and Tilman 2017; Lal 2001; de Ruiter et al. 2017; Poore and Nemecek 2018

Integrated response option	Description	Context and caveats	Supporting evidence
Integrated water management	Integrated water management is the process of creating holistic strategies to promote integrated, efficient, equitable and sustainable use of water for agroecosystems. It includes a collection of practices including water-use efficiency and irrigation in arid/semi-arid areas, improvement of soil health through increases in soil organic matter content, and improved cropland management, agroforestry and conservation agriculture. Increasing water availability, and reliability of water for agricultural production, can be achieved by using different techniques of water harvesting, storage, and its judicious utilisation through farm ponds, dams, and community tanks in rainfed agriculture areas can benefit adaptation.	These practices can reduce aquifer and surface water depletion, and prevent over-extraction, and the management of climate risks. Many technical innovations, e.g., precision water management, can have benefits for both adaptation and mitigation, although trade-offs are possible. Maintaining the same level of yield through use of site-specific water management-based approach could have benefits for both food security and mitigation.	Chapter 3; Chapter 4; Chapter 5 Brindha and Pavelic 2016; Jat et al. 2016; Jiang 2015; Keesstra et al. 2018; Liu et al. 2017; Nejad 2013; Rao et al. 2017b; Shaw et al. 2014; Sapkota et al. 2017; Scott et al. 2011; Waldron et al. 2017

Table 6.6 | Integrated response options based on land management in forests.

Integrated response option	Description	Context and caveats	Supporting evidence
Forest management	Forest management refers to management interventions in forests for the purpose of climate change mitigation. It includes a wide variety of practices affecting the growth of trees and the biomass removed, including improved regeneration (natural or artificial) and a better schedule, intensity and execution of operations (thinning, selective logging, final cut, reduced impact logging, etc.). Sustainable forest management is the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems.	Sustainable forest management can enhance the carbon stock in biomass, dead organic matter, and soil – while providing wood-based products to reduce emissions in other sectors through material and energy substitution. A trade-off exists between different management strategies: higher harvest decreases the carbon in the forest biomass in the short term but increases the carbon in wood products and the potential for substitution effects. Sustainable forest management, also through close-to-nature silvicultural techniques, can potentially offer many co-benefits in terms of climate change mitigation, adaptation, biodiversity conservation, microclimatic regulation, soil erosion protection, coastal area protection and water and flood regulation. Forest management strategies aimed at increasing the biomass stock levels may have adverse side effects, such as decreasing the stand-level structural complexity, biodiversity and resilience to natural disasters. Forest management also affects albedo and evapotranspiration.	Chapter 2; Chapter 4 D'Amato et al. 2011; Dooley and Kartha 2018; Ellison et al. 2017; Erb et al. 2017; Grassi et al. 2018; Griscom et al. 2017; Jantz et al. 2014; Kurz et al. 2016; Locatelli 2011; Luyssaert et al. 2018; Nabuurs et al. 2017; Naudts et al. 2016; Pingoud et al. 2018; Putz et al. 2012; Seidl et al. 2014; Smith et al. 2014; Smyth et al. 2014; Stanturf et al. 2015
Reduced deforestation and forest degradation	Reduced deforestation and forest degradation includes conservation of existing carbon pools in forest vegetation and soil by controlling the drivers of deforestation (i.e., commercial and subsistence agriculture, mining, urban expansion) and forest degradation (i.e., overharvesting including fuelwood collection, poor harvesting practices, overgrazing, pest outbreaks, and extreme wildfires), also through establishing protected areas, improving law enforcement, forest governance and land tenure, supporting community forest management and introducing forest certification.	Reducing deforestation and forest degradation is a major strategy to reduce global GHG emissions. The combination of reduced GHG emissions and biophysical effects results in a large climate mitigation effect, with benefits also at local level. Reduced deforestation preserves biodiversity and ecosystem services more efficiently and at lower costs than afforestation/reforestation. Efforts to reduce deforestation and forest degradation may have potential adverse side effects, for example, reducing availability of land for farming, restricting the rights and access of local people to forest resources (e.g., firewood), or increasing the dependence of local people to insecure external funding.	Chapter 2 Alkama and Cescatti 2016; Baccini et al. 2017; Barlow et al. 2016; Bayrak et al. 2016; Caplow et al. 2011; Curtis et al. 2018; Dooley and Kartha 2018; Griscom et al. 2017; Hansen et al. 2013; Hosonuma et al. 2012; Houghton et al. 2015; Lewis et al. 2015; Pelletier et al. 2016; Rey Benayas et al. 2009
Reforestation and forest restoration	Reforestation is the conversion to forest of land that has previously contained forests but that has been converted to some other use. Forest restoration refers to practices aimed at regaining ecological integrity in a deforested or degraded forest landscape. As such, it could fall under reforestation if it were re-establishing trees where they have been lost, or under forest management if it were restoring forests where not all trees have been lost. For practical reasons, here forest restoration is treated together with reforestation.	Reforestation is similar to afforestation with respect to the co-benefits and adverse side effects among climate change mitigation, adaptation, desertification, land degradation and food security (see row on Afforestation below). Forest restoration can increase terrestrial carbon stocks in deforested or degraded forest landscapes and can offer many co-benefits in terms of increased resilience of forests to climate change, enhanced connectivity between forest areas and conservation of biodiversity hotspots. Forest restoration may threaten livelihoods and local access to land if subsistence agriculture is targeted.	Chapter 2 Dooley and Kartha 2018; Ellison et al. 2017; Locatelli 2011; Locatelli et al. 2015b; Smith et al. 2014; Stanturf et al. 2015

Integrated response option	Description	Context and caveats	Supporting evidence
Afforestation	Afforestation is the conversion to forest of land that historically have not contained forests (see also 'reforestation').	Afforestation increases terrestrial carbon stocks but can also change the physical properties of land surfaces, such as surface albedo and evapotranspiration with implications for local and global climate. In the tropics, enhanced evapotranspiration cools surface temperatures, reinforcing the climate benefits of CO_2 sequestration in trees. At high latitudes and in areas affected by seasonal snow cover, the decrease in surface albedo after afforestation becomes dominant and causes an annual average warming that counteracts carbon benefits. Net biophysical effects on regional climate from afforestation is seasonal and can reduce the frequency of climate extremes, such as heat waves, improving adaptation to climate change and reducing the vulnerability of people and ecosystems. Afforestation helps to address land degradation and desertification, as forests tend to maintain water quality by reducing runoff, trapping sediments and nutrients, and improving groundwater recharge. However, food security could be hampered since an increase in global forest area can increase food prices through land competition. Other adverse side effects occur when afforestation is based on non-native species, especially with the risks related to the spread of exotic fast-growing tree species. For example, exotic species can upset the balance of evapotranspiration regimes, with negative impacts on water availability, particularly in dry regions.	Chapter 2; Chapter 3; Chapter 4; Chapter 5 Alkama and Cescatti 2016; Arora and Montenegro 2011; Bonan 2008; Boysen et al. 2017a; Brundu and Richardson 2016; Cherubini et al. 2017; Ciais et al. 2013; Ellison et al. 2017; Findell et al. 2017; Medugu et al. 2010; Kongsager et al. 2016; Kreidenweis et al. 2016; Lejeune et al. 2018; Li et al. 2015; Locatelli et al. 2015b; Perugini et al. 2017; Salvati et al. 2014; Smith et al. 2013, 2014; Trabucco et al. 2008

Table 6.7 | Integrated response options based on land management of soils.

Integrated response option	Description	Context and caveats	Supporting evidence
Increased soil organic carbon content	Practices that increase soil organic matter content include a) *land-use change* to an ecosystem with higher equilibrium soil carbon levels (e.g., from cropland to forest), b) *management of the vegetation*: including high input carbon practices, for example, improved varieties, rotations and cover crops, perennial cropping systems, biotechnology to increase inputs and recalcitrance of below ground carbon, c) *nutrient management and organic material input* to increase carbon returns to the soil, including: optimised fertiliser and organic material application rate, type, timing and precision application, d) *reduced tillage intensity and residue retention*, and e) *improved water management*: including irrigation in arid/semi-arid conditions.	Increasing soil carbon stocks removes CO_2 from the atmosphere and increases the water-holding capacity of the soil, thereby conferring resilience to climate change and enhancing adaptation capacity. It is a key strategy for addressing both desertification and land degradation. There is some evidence that crop yields and yield stability increase by increased organic matter content, though some studies show equivocal impacts. Some practices to increase soil organic matter stocks vary in their efficacy. For example, the impact of no-till farming and conservation agriculture on soil carbon stocks is often positive, but can be neutral or even negative, depending on the amount of crop residues returned to the soil. If soil organic carbon stocks were increased by increasing fertiliser inputs to increase productivity, emissions of nitrous oxide from fertiliser use could offset any climate benefits arising from carbon sinks. Similarly, if any yield penalty is incurred from practices aimed at increasing soil organic carbon stocks (e.g., through extensification), emissions could be increased through indirect land-use change, and there could also be adverse side effects on food security.	Bestelmeyer and Briske 2012; Cheesman et al. 2016; Frank et al. 2017; Gao et al. 2018; Hijbeek et al. 2017b; Keesstra et al. 2016; Lal 2016; Lambin and Meyfroidt 2011; de Moraes Sá et al. 2017; Palm et al. 2014; Pan et al. 2009; Paustian et al. 2016; Powlson et al. 2014, 2016; Schjønning et al. 2018; Smith et al. 2013, 2014, 2016c; Soussana et al. 2019; Steinbach and Alvarez 2006; VandenBygaart 2016
Reduced soil erosion	Soil erosion is the removal of soil from the land surface by water, wind or tillage, which occurs worldwide but it is particularly severe in Asia, Latin America and the Caribbean, and the Near East and North Africa. Soil erosion management includes conservation practices (e.g., the use of minimum tillage or zero tillage, crop rotations and cover crops, rational grazing systems), engineering-like practices (e.g., construction of terraces and contour cropping for controlling water erosion), or forest barriers and strip cultivation for controlling wind erosion. In eroded soils, the advance of erosion gullies and sand dunes can be limited by increasing plant cover, among other practices.	The fate of eroded soil carbon is uncertain, with some studies indicating a net source of CO_2 to the atmosphere and others suggesting a net sink. Reduced soil erosion has benefits for adaptation as it reduces vulnerability of soils to loss under climate extremes, increasing resilience to climate change. Some management practices implemented to control erosion, such as increasing ground cover, can reduce the vulnerability of soils to degradation/landslides, and prevention of soil erosion is a key measure used to tackle desertification. Because it protects the capacity of land to produce food, it also contributes positively to food security.	Chapter 3 Chen 2017; Derpsch et al. 2010; FAO and ITPS 2015; FAO 2015; Garbrecht et al. 2015; Jacinthe and Lal 2001; Lal and Moldenhauer 1987; Lal 2001; Lugato et al. 2016; de Moraes Sá et al. 2017; Poeplau and Don 2015; Smith et al. 2001, 2005; Stallard 1998; Van Oost et al. 2007

Integrated response option	Description	Context and caveats	Supporting evidence
Reduced soil salinisation	Soil salinisation is a major process of land degradation that decreases soil fertility and affects agricultural production, aquaculture and forestry. It is a significant component of desertification processes in drylands. Practices to reduce soil salinisation include improvement of water management (e.g., water-use efficiency and irrigation/drainage technology in arid/semi-arid areas, surface and groundwater management), improvement of soil health (through increase in soil organic matter content) and improved cropland, grazing land and livestock management, agroforestry and conservation agriculture.	Techniques to prevent and reverse soil salinisation may have small benefits for mitigation by enhancing carbon sinks. These techniques may benefit adaptation and food security by maintaining existing crop systems and closing yield gaps for rainfed crops. These techniques are central to reducing desertification and land degradation, since soil salinisation is a primary driver of both.	Section 3.6; Chapter 4; Chapter 5 Baumhardt et al. 2015; Dagar et al. 2016; Datta et al. 2000; DERM 2011; Evans and Sadler 2008; He et al. 2015; D'Odorico et al. 2013; Kijne et al. 1988; Qadir et al. 2013; Rengasamy 2006; Singh 2009; UNCTAD 2011; Wong et al. 2010
Reduced soil compaction	Reduced soil compaction mainly includes agricultural techniques (e.g., crop rotations, control of livestock density) and control of agricultural traffic.	Techniques to reduce soil compaction have variable impacts on GHG emissions but may benefit adaptation by improving soil climatic resilience. Since soil compaction is a driver of both desertification and land degradation, a reduction of soil compaction could benefit both. It could also help close yield gaps in rainfed crops.	Chamen et al. 2015; Epron et al. 2016; FAO and ITPS 2015; Hamza and Anderson 2005; Soane and Van Ouwerkerk 1994; Tullberg et al. 2018
Biochar addition to soil	The use of biochar, a solid product of the pyrolysis process, as a soil amendment increases the water-holding capacity of soil. It may therefore provide better access to water and nutrients for crops and other vegetation types (so can form part of cropland, grazing land and forest management).	The use of biochar increases carbon stocks in the soil. It can enhance yields in the tropics (but less so in temperate regions), thereby benefitting both adaptation and food security. Since it can improve soil water-holding capacity and nutrient-use efficiency, and can ameliorate heavy metal pollution and other impacts, it can benefit desertification and land degradation. The positive impacts could be tempered by additional pressure on land if large quantities of biomass are required as feedstock for biochar production.	Chapter 2; Chapter 3; Chapter 4; Chapter 5 Jeffery et al. 2017; Smith 2016; Sohi 2012; Woolf et al. 2010

Table 6.8 | Integrated response options based on land management of all/other ecosystems.

Integrated response option	Description	Context and caveats	Supporting evidence
Fire management	Fire management is a land management option aimed at safeguarding life, property and resources through the prevention, detection, control, restriction and suppression of fire in forest and other vegetation. It includes the improved use of fire for sustainable forestry management, including wildfire prevention and prescribed burning. Prescribed burning is used to reduce the risk of large, uncontrollable fires in forest areas, and controlled burning is among the most effective and economic methods of reducing fire danger and stimulating natural reforestation under the forest canopy and after clear felling.	The frequency and severity of large wildfires have increased around the globe in recent decades, which has impacted on forest carbon budgets. Fire can cause various GHG emissions such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and others such as carbon monoxide (CO), volatile organic carbon, and smoke aerosols. Fire management can reduce GHG emissions and can reduce haze pollution, which has significant health and economic impacts. Fire management helps to prevent soil erosion and land degradation and is used in rangelands to conserve biodiversity and to enhance forage quality.	Chapter 2; Cross-Chapter Box 3 in Chapter 2 Esteves et al. 2012; FAO 2006; Lin et al. 2017; O'Mara 2012; Rulli et al. 2006; Scasta et al. 2016; Seidl et al. 2014; Smith et al. 2014; Tacconi 2016; Valendik et al. 2011; Westerling et al. 2006; Whitehead et al. 2008; Yong and Peh 2016
Reduced landslides and natural hazards	Landslides are mainly triggered by human activity (e.g., legal and illegal mining, fire, deforestation) in combination with climate. Management of landslides and natural hazards (e.g., floods, storm surges, droughts) is based on vegetation management (e.g., afforestation) and engineering works (e.g., dams, terraces, stabilisation and filling of erosion gullies).	Management of landslides and natural hazards is important for adaptation and is a crucial intervention for managing land degradation, since landslides and natural hazards are among the most severe degradation processes. In countries where mountain slopes are planted with food crops, reduced landslides will help deliver benefits for food security. Most deaths caused due to different disasters have occurred in developing countries, where poverty, poor education and health facilities and other aspects of development, increase exposure, vulnerability and risk.	Noble et al. 2014; Arnáez J et al. 2015; Campbell 2015; FAO and ITPS 2015; Gariano and Guzzetti 2016; Mal et al. 2018
Reduced pollution including acidification	Management of air pollution is connected to climate change by emission sources of air-polluting materials and their impacts on climate, human health and ecosystems, including agriculture. Acid deposition is one of the many consequences of air pollution, harming trees and other vegetation, as well as being a significant driver of land degradation. Practices that reduce acid deposition include prevention of emissions of nitrogen oxides (NOx) and sulphur dioxide (SO_2), which also reduce GHG emissions and other short-lived climate pollutants (SLCPs). Reductions of SLCPs reduce warming in the near term and the overall rate of warming, which can be crucial for plants that are sensitive to even small increases in temperature.	There are a few potential adverse side effects of reduction in air pollution to carbon sequestration in terrestrial ecosystems, because some forms of air pollutants can enhance crop productivity by increasing diffuse sunlight, compared to direct sunlight. Reactive nitrogen deposition could also enhance CO_2 uptake in boreal forests and increase soil carbon pools to some extent. Air pollutants have different impacts on climate depending primarily on the composition, with some aerosols (and clouds seeded by them) increasing the reflection of solar radiation to space leading to net cooling, while others (e.g., black carbon and tropospheric ozone) having a net warming effect. Therefore, control of these different pollutants will have both positive and negative impacts on climate mitigation.	Chapter 2 Anderson et al. 2017; Chum et al. 2011; Carter et al. 2015; Coakley 2005; Maaroufi et al. 2015; Markandya et al. 2018; Melamed and Schmale 2016; Mostofa et al. 2016; Nemet et al. 2010; Ramanathan et al. 2001; Seinfeld and Pandis; Smith et al. 2015; UNEP 2017; UNEP and WMO 2011; Wild et al. 2012; Xu et al. 2013; Xu and Ramanathan 2017

Integrated response option	Description	Context and caveats	Supporting evidence
Reduced pollution including acidification *continued*	Management of harmful air pollutants such as fine particulate matter ($PM_{2.5}$) and ozone (O_3) also mitigate the impacts of incomplete fossil fuel combustion and GHG emissions. In addition, management of pollutants such as tropospheric O_3 has beneficial impacts on food production, since O_3 decreases crop production. Control of urban and industrial air pollution would also mitigate the harmful effects of pollution and provide adaptation co-benefits *via* improved human health. Management of pollution contributes to aquatic ecosystem conservation since controlling air pollution, rising atmospheric CO_2 concentrations, acid deposition, and industrial waste will reduce acidification of marine and freshwater ecosystems.		
Management of invasive species/ encroachment	Agriculture and forests can be diverse, but often much of the diversity is non-native. Invasive species in different biomes have been introduced intentionally or unintentionally through export of ornamental plants or animals, and through the promotion of modern agriculture and forestry. Non-native species tend to be more numerous in larger than in smaller human-modified landscapes (e.g., over 50% of species in an urbanised area or extensive agricultural fields can be non-native). Invasive alien species in the USA cause major environmental damage amounting to almost 120 billion USD yr^{-1}. There are approximately 50,000 foreign species and the number is increasing. About 42% of the species on the Threatened or Endangered species lists are at risk primarily because of alien-invasive species. Invasive species can be managed through manual clearance of invasive species, while in some areas, natural enemies of the invasive species are introduced to control them.	Exotic species are used in forestry where local indigenous forests cannot produce the type, quantity and quality of forest products required. Planted forests of exotic tree species make significant contributions to the economy and provide multiple products and Nature's Contributions to People. In general, exotic species are selected to have higher growth rates than native species and produce more wood per unit of area and time. In 2015, the total area of planted forest with non-native tree species was estimated to be around 0.5 Mkm^2. Introduced species were dominant in South America, Oceania and Eastern and Southern Africa, where industrial forestry is dominant. The use of exotic tree species has played an important role in the production of roundwood, fibre, firewood and other forest products. The challenge is to manage existing and future plantation forests of alien trees to maximise current benefits, while minimising present and future risks and negative impacts, and without compromising future benefits. In many countries or regions, non-native trees planted for production or other purposes often lead to sharp conflicts of interest when they become invasive, and to negative impacts on Nature's Contributions to People and nature conservation.	Brundu and Richardson 2016; Cossalter and Pye-Smith 2003; Dresner et al. 2015; Payn et al. 2015; Pimentel et al. 2005; Vilà et al. 2011
Restoration and reduced conversion of coastal wetlands	Coastal wetland restoration involves restoring degraded/ damaged coastal wetlands, including mangroves, salt marshes and seagrass ecosystems.	Coastal wetland restoration and avoided coastal wetland impacts have the capacity to increase carbon sinks and can provide benefits by regulating water flow and preventing downstream flooding. Coastal wetlands provide a natural defence against coastal flooding and storm surges by dissipating wave energy, reducing erosion and by helping to stabilise shore sediments. Since large areas of global coastal wetlands are degraded, restoration could provide benefits land degradation. Since some areas of coastal wetlands are used for food production, restoration could displace food production and damage local food supply (Section 6.3.4), though some forms (e.g., mangrove restoration) can improve local fisheries.	Griscom et al. 2017; Lotze et al. 2006; Munang et al. 2014; Naylor et al. 2000
Restoration and reduced conversion of peatlands	Peatland restoration involves restoring degraded/ damaged peatlands, which both increases carbon sinks, but also avoids ongoing CO_2 emissions from degraded peatlands. So, as well as protecting biodiversity, it both prevents future emissions and creates a sink.	Avoided peat impacts and peatland restoration can provide significant mitigation, though restoration can lead to an increase in methane emissions, particularly in nutrient rich fens. There may also be benefits for climate adaptation by regulating water flow and preventing downstream flooding. Considering that large areas of global peatlands are degraded, peatland restoration is a key tool in addressing land degradation. Since large areas of tropical peatlands and some northern peatlands have been drained and cleared for food production, their restoration could displace food production and damage local food supply, potentially leading to adverse impacts on food security locally, though the global impact would be limited due to the relatively small areas affected.	Griscom et al. 2017; Jauhiainen et al. 2008; Limpens et al. 2008; Munang et al. 2014

Integrated response option	Description	Context and caveats	Supporting evidence
Biodiversity conservation	Biodiversity conservation refers to practices aimed at maintaining components of biological diversity. It includes conservation of ecosystems and natural habitats, maintenance and recovery of viable populations of species in their natural surroundings (*in-situ* conservation) and, in the case of domesticated or cultivated species, in the surroundings where they have developed their distinctive properties outside their natural habitats (*ex-situ* conservation). Examples of biodiversity conservation measures are establishment of protected areas to achieve specific conservation objectives, preservation of biodiversity hotspots, land management to recover natural habitats, interventions to expand or control selective plant or animal species in productive lands or rangelands (e.g., rewilding).	Biodiversity conservation measures interact with the climate system through many complex processes, which can have either positive or negative impacts. For example, establishment of protected areas can increase carbon storage in vegetation and soil, and tree planting to promote species richness and natural habitats can enhance carbon uptake capacity of ecosystems. Management of wild animals can influence climate *via* emissions of GHGs (from anaerobic fermentation of plant materials in the rumen), impacts on vegetation (*via* foraging), changes in fire frequency (as grazers lower grass and vegetation densities as potential fuels), and nutrient cycling and transport (by adding nutrients to soils). Conserving and restoring megafauna in northern regions also prevents thawing of permafrost and reduces woody encroachment, thus avoiding methane emissions and increases in albedo. Defaunation affects carbon storage in tropical forests and savannahs. In the tropics, the loss of mega-faunal frugivores is estimated be responsible for up to 10% reduction in carbon storage of global tropical forests. Frugivore rewilding programmes in the tropics are seen as carbon sequestration options that can be equally effective as tree planting schemes. Biodiversity conservation measures generally favour adaptation, but can interact with food security, land degradation or desertification. Protected areas for biodiversity reduce the land available for food production, and abundancies of some species (such as large animals) can influence land degradation processes by grazing, trampling and compacting soil surfaces, thereby altering surface temperatures and chemical reactions affecting sediment and carbon retention.	Bello et al. 2015; Campbell et al. 2008; Cromsigt et al. 2018; Kapos et al. 2008; Osuri et al. 2016; Schmitz et al. 2018; Secretariat of the Convention on Biological Diversity 2008

Table 6.9 | Integrated response options based on land management specifically for carbon dioxide removal (CDR).

Integrated response option	Description	Context and caveats	Supporting evidence
Enhanced weathering of minerals	The enhanced weathering of minerals that naturally absorb CO_2 from the atmosphere has been proposed as a CDR technology with a large mitigation potential. The rocks are ground to increase the surface area and the ground minerals are then applied to the land where they absorb atmospheric CO_2.	Enhanced mineral weathering can remove atmospheric carbon dioxide (CO_2). Since ground minerals can increase pH, there could be some benefits for efforts to prevent or reverse land degradation where acidification is the driver of degradation. Since increasing soil pH in acidified soils can increase productivity, the same effect could provide some benefit for food security. Minerals used for enhanced weathering need to be mined, and mining has large impacts locally, though the total area mined is likely to be small on the global scale.	Beerling et al. 2018; Lenton 2010; Schuiling and Krijgsman 2006; Smith et al. 2016a; Taylor et al. 2016
Bioenergy and bioenergy with carbon capture and storage (BECCS)	Bioenergy production can mitigate climate change by delivering an energy service, therefore avoiding combustion of fossil energy. It is the most common renewable energy source used in the world today and has a large potential for future deployment (see Cross-Chapter Box 7 in this chapter). BECCS entails the use of bioenergy technologies (e.g., bioelectricity or biofuels) in combination with CO_2 capture and storage (see also Glossary). BECCS simultaneously provides energy and can reduce atmospheric CO_2 concentrations (Chapter 2; Cross-Chapter Box 7 in this chapter) for a discussion of potentials and atmospheric effects); thus, BECCS is considered a CDR technology. While several BECCS demonstration projects exist, it has yet to be deployed at scale. Bioenergy and BECCS are widely-used in many future scenarios as a climate change mitigation option in the energy and transport sector, especially those scenarios aimed at a stabilisation of global climate at 2°C or less above pre-industrial levels.	Bioenergy and BECCS can compete for land and water with other uses. Increased use of bioenergy and BECCS can result in large expansion of cropland area, significant deforestation, and increased irrigation water use and water scarcity. Large-scale use of bioenergy can result in increased food prices and can lead to an increase in the population at risk of hunger. As a result of these effects, large-scale bioenergy and BECCS can have negative impacts for food security. Interlinkages of bioenergy and BECCS with climate change adaptation, land degradation, desertification, and biodiversity are highly dependent on local factors such as the type of energy crop, management practice, and previous land use. For example, intensive agricultural practices aiming to achieve high crop yields, as is the case for some bioenergy systems, may have significant effects on soil health, including depletion of soil organic matter, resulting in negative impacts on land degradation and desertification. However, with low inputs of fossil fuels and chemicals, limited irrigation, heat/drought tolerant species, using marginal land, biofuel programmes can be beneficial to future adaptation of ecosystems.	Cross-Chapter Box 7 in Chapter 6 IPCC SR15 (IPCC 2018); Chapter 2; Chapter 4; Section 6.4; Chapter 7 Baker et al. 2019; Calvin et al. 2014; Chaturvedi et al. 2013; Chum et al. 2011; Clarke et al. 2014; Correa et al. 2017; Creutzig et al. 2015; Dasgupta et al. 2014; Don et al. 2012; Edelenbosch et al. 2017; IPCC 2012; Favero and Mendelsohn 2014; FAO 2011a; Fujimori et al. 2019; Fuss et al. 2016, 2018; Hejazi et al. 2015; Kemper 2015; Kline et al. 2017; Lal 2014; Lotze-Campen et al. 2013; Mello et al. 2014; Muratori et al. 2016; Noble et al. 2014; Obersteiner et al. 2016;

Integrated response option	Description	Context and caveats	Supporting evidence
Bioenergy and bioenergy with carbon capture and storage (BECCS) *continued*		Planting bioenergy crops, like perennial grasses, on degraded land can increase soil carbon and ecosystem quality (including biodiversity), thereby helping to preserve soil quality, reverse land degradation, prevent desertification processes, and reduce food insecurity. These effects depend on the scale of deployment, the feedstock, the prior land use, and which other response options are included (see Section 6.4.4.2). Large-scale production of bioenergy can require significant amounts of land, increasing potential pressures for land conversion and land degradation. Low levels of bioenergy deployment require less land, leading to smaller effects on forest cover and food prices; however, these land requirements could still be substantial. In terms of feedstocks, in some regions, they may not need irrigation, and thus would not compete for water with food crops. Additionally, the use of residues or microalgae could limit competition for land and biodiversity loss; however, residues could result in land degradation or decreased soil organic carbon. Whether woody bioenergy results in increased competition for land or not is disputed in the literature, with some studies suggesting reduced competition and others suggesting enhanced competition. One study noted that this effect changes over time, with complementarity between woody bioenergy and forest carbon sequestration in the near-term, but increased competition for land with afforestation/reforestation in the long term. Additionally, woody bioenergy could also result in land degradation.	Popp et al. 2011b, 2014, 2017; Riahi et al. 2017; Robertson et al. 2017a; Sánchez et al. 2017; Searchinger et al. 2018; Sims et al. 2014; Slade et al. 2014; Smith et al. 2016c; Tian et al. 2018; Torvanger 2018; Van Vuuren et al. 2011, 2015, 2016; Wise et al. 2015

6.2.2 Integrated response options based on value chain management

6.2.2.1 Integrated response options based on value chain management through demand management

Integrated response options based on value chain management through demand management are described in Table 6.10, which also notes any context specificities, and provides the evidence base for the effects of the response options.

6.2.2.2 Integrated response options based on value chain management through supply management

Integrated response options based on value chain management through supply management are described in Table 6.11, which also notes any context specificities, and provides the evidence base in for effects of the response options.

6.2.3 Integrated response options based on risk management

6.2.3.1 Risk management options

Integrated response options based on risk management are described in Table 6.12, which also notes any context specificities, and provides the evidence base for the effects of the response options.

Table 6.10 | Integrated response options based on value chain management through demand management.

Integrated response option	Description	Context and caveats	Supporting evidence
Dietary change	Sustainable healthy diets represent a range of dietary changes to improve human diets, to make them healthy in terms of the nutrition delivered, and also (economically, environmentally and socially) sustainable. A 'contract and converge' model of transition to sustainable healthy diets would involve a reduction in over-consumption (particularly of livestock products) in over-consuming populations, with increased consumption of some food groups in populations where minimum nutritional needs are not met. Such a conversion could result in a decline in undernourishment, as well as reduction in the risk of morbidity and mortality due to over-consumption.	A dietary shift away from meat can reduce GHG emissions, reduce cropland and pasture requirements, enhance biodiversity protection, and reduce mitigation costs. Additionally, dietary change can both increase potential for other land-based response options and reduce the need for them by freeing land. By decreasing pressure on land, demand reduction through dietary change could also allow for decreased production intensity, which could reduce soil erosion and provide benefits to a range of other environmental indicators such as deforestation and decreased use of fertiliser (nitrogen and phosphorus), pesticides, water and energy, leading to potential benefits for adaptation, desertification, and land degradation.	Chapter 5; Section 6.4.4.2 Aleksandrowicz et al. 2016; Bajželj et al. 2014a; Bonsch et al. 2016; Erb et al. 2016; Godfray et al. 2010; Haberl et al. 2011; Havlík et al. 2014; Muller et al. 2017; Smith et al. 2013; Springmann et al. 2018; Stehfest et al. 2009; Tilman and Clark 2014; Wu et al. 2019
Reduced post-harvest losses	Approximately one-third of the food produced for human consumption is wasted in post-production operations. Most of these losses are due to poor storage management. Post-harvest food losses underlie the food system's failure to equitably enable accessible and affordable food in all countries. Reduced post-harvest food losses can improve food security in developing countries (while food loss in developed countries mostly occurs at the retail/consumer stage). The key drivers for post-harvest waste in developing countries are structural and infrastructure deficiencies. Thus, reducing food waste at the post-harvest stage requires responses that process, preserve and, where appropriate, redistribute food to where it can be consumed immediately.	Differences exist between farm food waste reduction technologies between small-scale agricultural systems and large-scale agricultural systems. A suite of options includes farm-level storage facilities, trade or exchange processing technologies including food drying, on-site farm processing for value addition, and improved seed systems. For large-scale agri-food systems, options include cold chains for preservation, processing for value addition and linkages to value chains that absorb the harvests almost instantly into the supply chain. In addition to the specific options to reduce food loss and waste, there are more systemic possibilities related to food systems. Improving and expanding the 'dry chain' can significantly reduce food losses at the household level. Dry chains are analogous to the cold chain and refers to the 'initial dehydration of durable commodities to levels preventing fungal growth' followed by storage in moisture-proof containers. Regional and local food systems are now being promoted to enable production, distribution, access and affordability of food. Reducing post-harvest losses has the potential to reduce emissions and could simultaneously reduce food costs and increase availability. The perishability and safety of fresh foods are highly susceptible to temperature increase.	Chapter 5 Ansah et al. 2017; Bajželj et al. 2014b; Billen et al. 2018; Bradford et al. 2018; Chaboud and Daviron 2017; Göbel et al. 2015; Gustavsson et al. 2011; Hengsdijk and de Boer 2017; Hodges et al. 2011; Ingram et al. 2016; Kissinger et al. 2018; Kumar and Kalita 2017; Ritzema et al. 2017; Sheahan and Barrett 2017a; Wilhelm et al. 2016)
Reduced food waste (consumer or retailer)	Since approximately 9–30% of all food is wasted, reducing food waste can reduce pressure on land (see also reducing post-harvest losses).	Reducing food waste could lead to a reduction in cropland area and GHG emissions, resulting in benefits for mitigation. By decreasing pressure on land, food waste reduction could allow for decreased production intensity, which could reduce soil erosion and provide benefits to a range of other environmental indicators such as deforestation and decreases in use of fertiliser (N and P), pesticides, water and energy, leading to potential benefits for adaptation, desertification, and land degradation.	Alexander et al. 2016; Bajželj et al. 2014b; Gustavsson et al. 2011; Kummu et al. 2012; Muller et al. 2017; Smith et al. 2013; Vermeulen et al. 2012b
Material substitution	Material substitution involves the use of wood or agricultural biomass (e.g., straw bales) instead of fossil fuel-based materials (e.g., concrete, iron, steel, aluminium) for building, textiles or other applications.	Material substitution reduces carbon emissions – both because the biomass sequesters carbon in materials while re-growth of forests can lead to continued sequestration, and because it reduces the demand for fossil fuels, delivering a benefit for mitigation. However, a potential trade-off exists between conserving carbon stocks and using forests for wood products. If the use of material for substitution was large enough to result in increased forest area, then the adverse side effects for adaptation and food security would be similar to that of reforestation and afforestation. In addition, some studies indicate that wooden buildings, if properly constructed, could reduce fire risk compared to steel, creating a co-benefit for adaptation. The effects of material substitution on land degradation depend on management practice; some forms of logging can lead to increased land degradation. Long-term forest management with carbon storage in long-lived products also results in atmospheric CO_2 removal.	Chapter 4 Dugan et al. 2018; Eriksson et al. 2012; Gustavsson et al. 2006; Iordan et al. 2018; Kauppi et al. 2018; Kurz et al. 2016; Leskinen et al. 2018; McLaren 2012; Miner 2010; Oliver and Morecroft 2014; Ramage et al. 2017; Sathre and O'Connor 2010; Smyth et al. 2014

Table 6.11 | Integrated response options based on value chain management through supply management.

Integrated response option	Description	Context and caveats	Supporting evidence
Sustainable sourcing	Sustainable sourcing includes approaches to ensure that the production of goods is done in a sustainable way, such as through low-impact agriculture, zero-deforestation supply chains, or sustainably harvested forest products. Currently around 8% of global forest area has been certified in some manner, and 25% of global industrial roundwood comes from certified forests. Sustainable sourcing also aims to enable producers to increase their percentage of the final value of commodities. Adding value to products requires improved innovation, coordination and efficiency in the food supply chain, as well as labelling to meet consumer demands. As such, sustainable sourcing is an approach that combines both supply- and demand-side management. Promoting sustainable and value-added products can reduce the need for compensatory extensification of agricultural areas and is a specific commitment of some sourcing programmes (such as forest certification programmes). Table 7.3 (Chapter 7) provides examples of the many sustainable sourcing programmes now available globally.	Sustainable sourcing is expanding but accounts for only a small fraction of overall food and material production; many staple food crops do not have strong sustainability standards. Sustainable sourcing provides potential benefits for both climate mitigation and adaptation by reducing drivers of unsustainable land management, and by diversifying and increasing flexibility in the food system to climate stressors and shocks. Sustainable sourcing can lower expenditure for food processors and retailers by reducing losses. Adding value to products can extend a producer's marketing season and provide unique opportunities to capture niche markets, thereby increasing their adaptive capacity to climate change. Sustainable sourcing can also provide significant benefits for food security, while simultaneously creating economic alternatives for the poor. Sustainable sourcing programmes often also have positive impacts on the overall efficiency of the food supply chain and can create closer and more direct links between producers and consumers. In some cases, processing of value-added products could lead to higher emissions or demand for resources in the food system, potentially leading to small adverse impacts on land degradation and desertification challenges.	Chapter 2; Chapter 3; Chapter 5; Section 6.4 Accorsi et al. 2017; Bajželj et al. 2014a; Bustamante et al. 2014; Clark and Tilman 2017; Garnett 2011; Godfray et al. 2010; Hertel 2015; Ingram et al. 2016; James and James 2010; Muller et al. 2017; Springer et al. 2015; Tayleur et al. 2017; Tilman and Clark 2014
Management of supply chains	Management of supply chains include a set of polycentric governance processes focused on improving efficiency and sustainability across the supply chain for each product, to reduce climate risk and profitably reduce emissions. Trade-driven food supply chains are becoming increasingly complex and are contributing to emissions. Improved management of supply chains can include 1) better food transport and increasing the economic value or reduce risks of commodities through production processes (e.g., packaging, processing, cooling, drying, extracting) and 2) improved policies for stability of food supply, as globalised food systems and commodity markets are vulnerable to food price volatility. The 2007–2008 food price shocks negatively affected food security for millions, most severely in Sub-Saharan Africa. Increasing the stability of food supply chains is a key goal to increase food security, given that climate change threatens to lead to more production shocks in the future.	Successful implementation of supply chain management practices is dependent on organisational capacity, the agility and flexibility of business strategies, the strengthening of public-private policies and effectiveness of supply-chain governance. Existing practices include a) greening supply chains (e.g., utilising products and services with a reduced impact on the environment and human health), b) adoption of specific sustainability instruments among agri-food companies (e.g., eco-innovation practices), c) adopting emission accounting tools (e.g., carbon and water foot-printing), and d) implementing 'demand forecasting' strategies (e.g., changes in consumer preference for 'green' products). In terms of food supply, measures to improve stability in traded markets can include i) financial and trade policies, such as reductions on food taxes and import tariffs, (ii) shortening food supply chains (SFSCs), (iii) increasing food production, (iv) designing alternative distribution networks, (v) increasing food market transparency and reducing speculation in futures markets, (vi) increasing storage options, and (vii) increasing subsidies and food-based safety nets.	Chapter 5 Barthel and Isendahl 2013; Haggblade et al. 2017; Lewis and Witham 2012; Michelini et al. 2018; Minot 2014; Mundler and Rumpus 2012; Tadasse et al. 2016; Wheeler and von Braun 2013; Wilhelm et al. 2016; Wodon and Zaman 2010; World Bank 2011
Enhanced urban food systems	Urban areas are becoming the principal territories for intervention in improving food access through innovative strategies that aim to reduce hunger and improve livelihoods. Interventions include urban and peri-urban agriculture and forestry and local food policy and planning initiatives such as Food Policy Councils and city-region-wide regional food strategies. Such systems have demonstrated inter-linkages of the city and its citizens with surrounding rural areas to create sustainable, and more nutritious food supplies for the city, while improving the health status of urban dwellers, reducing pollution levels, adapting to and mitigating climate change, and stimulating economic development. Options include support for urban and peri-urban agriculture, green infrastructure (e.g., green roofs), local markets, enhanced social (food) safety nets and development of alternative food sources and technologies, such as vertical farming.	Urban territorial areas have a potential to reduce GHG emissions through improved food systems to reduce vehicle miles of food transportation, localised carbon capture and food waste reduction. The benefits of urban food forests that are intentionally planted woody perennial food-producing species, are also cited for their carbon sequestration potentials. However, new urban food systems may have diverse and unexpected adverse side effects with climate systems, such as lower efficiencies in food supply and higher costs than modern large-scale agriculture. Diversifying markets, considering value-added products in the food supply system may help to improve food security by increasing its economic performance and revenues to local farmers.	Akhtar et al. 2016; Benis and Ferrão 2017; Brinkley et al. 2013; Chappell et al. 2016; Dubbeling 2014; Goldstein et al. 2016; Kowalski and Conway 2018; Lee-Smith 2010; Barthel and Isendahl 2013; Lwasa et al. 2014, 2015; Revi et al. 2014; Specht et al. 2014; Tao et al. 2015

Integrated response option	Description	Context and caveats	Supporting evidence
Improved food processing and retailing	Improved food processing and retailing involves several practices related to a) greening supply chains (e.g., utilising products and services with a reduced impact on the environment and human health), b) adoption of specific sustainability instruments among agri-food companies (e.g., eco-innovation practices), c) adopting emission accounting tools (e.g., carbon and water foot-printing), d) implementing 'demand forecasting' strategies (e.g., changes in consumer preference for 'green' products) and, e) supporting polycentric supply-chain governance processes.	Improved food processing and retailing can provide benefits for climate mitigation since GHG-friendly foods can reduce agri-food GHG emissions from transportation, waste and energy use. In cases where climate extremes and natural disasters disrupt supply chain networks, improved food processing and retailing can benefit climate adaptation by buffering the impacts of changing temperature and rainfall patterns on upstream agricultural production. It can provide benefits for food security by supporting healthier diets and reducing food loss and waste. Successful implementation is dependent on organisational capacity, the agility and flexibility of business strategies, the strengthening of public-private policies and effectiveness of supply-chain governance.	Chapter 2; Chapter 5 Avetisyan et al. 2014; Garnett et al. 2013; Godfray et al. 2010; Mohammadi et al. 2014; Porter et al. 2016; Ridoutt et al. 2016; Song et al. 2017
Improved energy use in food systems	Agriculture's energy efficiency can be improved to reduce the dependency on non-renewable energy sources. This can be realised either by decreased energy inputs, or through increased outputs per unit of input. In some countries, managerial inefficiency (rather than a technology gap) is the main source for energy-efficiency loss. Heterogenous patterns of energy efficiency exist at the national scale and promoting energy-efficient technologies along with managerial capacity development can reduce the gap and provide large benefits for climate adaptation. Improvements in carbon monitoring and calculation techniques such as the foot-printing of agricultural products can enhance energy-efficiency transition management and uptake in agricultural enterprises.	Transformation to low-carbon technologies such as renewable energy and energy efficiency can offer opportunities for significant climate change mitigation, for example, by providing a substitute to transport fuel that could benefit marginal agricultural resources, while simultaneously contributing to long-term economic growth. In poorer nations, increased energy efficiency in agricultural value-added production, in particular, can provide large mitigation benefits. Under certain scenarios, the efficiency of agricultural systems can stagnate and could exert pressure on grasslands and rangelands, thereby impacting on land degradation and desertification. Rebound effects can also occur, with adverse impacts on emissions.	Al-Mansour F and Jejcic V 2017; Baptista et al. 2013; Begum et al. 2015; Gunatilake et al. 2014; Jebli and Youssef 2017; Van Vuuren et al. 2017b

Table 6.12 | Integrated response options based on risk management.

Integrated response option	Description	Context and caveats	Supporting evidence
Management of urban sprawl	Unplanned urbanisation leading to sprawl and extensification of cities along the rural-urban fringe has been identified as a driver of forest and agricultural land loss and a threat to food production around cities. It has been estimated that urban expansion will result in a 1.8–2.4% loss of global croplands by 2030. This rapid urban expansion is especially strong in new emerging towns and cities in Asia and Africa. Policies to prevent such urbanisation have included integrated land-use planning, agricultural zoning ordinances and agricultural districts, urban redevelopment, arable land reclamation, and transfer/purchase of development rights or easements.	The prevention of uncontrolled urban sprawl may provide adaptation co-benefits, but adverse side effects for adaptation might arise due to restricted ability of people to move in response to climate change.	Barbero-Sierra et al. 2013; Bren d'Amour et al. 2016; Cai et al. 2013; Chen 2007; Francis et al. 2012; Gibson et al. 2015; Lee et al. 2015; Qian et al. 2015; Shen et al. 2017; Tan et al. 2009
Livelihood diversification	When households' livelihoods depend on a small number of sources of income without much diversification, and when those income sources are in fields that are highly climate dependent, like agriculture and fishing, this dependence can put food security and livelihoods at risk. Livelihood diversification (drawing from a portfolio of dissimilar sources of livelihood as a tool to spread risk) has been identified as one option to increase incomes and reduce poverty, increase food security, and promote climate resilience and risk reduction.	Livelihood diversification offers benefits for desertification and land degradation, particularly through non-traditional crops or trees in agroforestry systems which improve soil. Livelihood diversification may increase on-farm biodiversity due to these investments in more ecosystem-mimicking production systems, like agroforestry and polycultures. Diversification into non-agricultural fields, such as wage labour or trading, is increasingly favoured by farmers as a low-cost strategy, particularly to respond to increasing climate risks.	Adger 1999; Ahmed and Stepp 2016; Antwi-Agyei et al. 2014; Barrett et al. 2001; Berman et al. 2012; Bryceson 1999; DiGiano and Racelis 2012; Ellis 1998, 2008; Little et al. 2001; Ngigi et al. 2017; Rakodi 1999; Thornton and Herrero 2014
Use of local seeds	Using local seeds (also called seed sovereignty) refers to use of non-improved, non-commercial seeds varieties. These can be used and stored by local farmers as low-cost inputs and can often help contribute to the conservation of local varieties and landraces, increasing local biodiversity. Many local seeds also require no pesticide or fertiliser use, leading to less land degradation in their use.	Use of local seeds is important in the many parts of the developing world that do not rely on commercial seed inputs. Promotion of local seed-saving initiatives can include seed networks, banks and exchanges, and non-commercial open source plant breeding. These locally developed seeds can help protect local agrobiodiversity and can often be more climate resilient than generic commercial varieties, although the impacts on food security and overall land degradation are inconclusive.	Bowman 2015; Campbell and Veteto 2015; Coomes et al. 2015; Kloppenberg 2010; Luby et al. 2015; Van Niekerk and Wynberg 2017; Patnaik et al. 2017; Reisman 2017; Vasconcelos et al. 2013; Wattnem 2016

Integrated response option	Description	Context and caveats	Supporting evidence
Disaster risk management	Disaster risk management encompasses many approaches to try to reduce the consequences of climate- and weather-related disasters and events on socio-economic systems. The Hyogo Framework for Action is a UN framework for nations to build resilience to disasters through effective integration of disaster risk considerations into sustainable development policies. For example, in Vietnam a national strategy on disasters based on Hyogo has introduced the concept of a 'four-on-the-spot' approach for disaster risk management of: proactive prevention, timely response, quick and effective recovery, and sustainable development. Other widespread approaches to disaster risk management include using early warning systems that can encompass 1) education systems, 2) hazard and risk maps, 3) hydrological and meteorological monitoring (such as flood forecasting or extreme weather warnings), and 4) communications systems to pass on information to enable action. These approaches have long been considered to reduce the risk of household asset damage during one-off climate events and are increasingly being combined with climate adaptation policies.	Community-based disaster risk management has been pointed to as one of the most successful ways to ensure that information reaches the people who need to be participants in risk reduction. Effective disaster risk management approaches must be 'end-to-end,' reaching communities at risk and supporting and empowering vulnerable communities to take appropriate action. The most effective early warning systems are not simply technical systems of information dissemination, but utilise and develop community capacities, create local ownership of the system, and are based on a shared understanding of needs and purpose. Tapping into existing traditional or local knowledge has also been recommended for disaster risk management approaches to reducing vulnerability.	Ajibade and McBean 2014; Alessa et al. 2016; Bouwer et al. 2014; Carreño et al. 2007; Cools et al. 2016; Djalante et al. 2012; Garschagen 2016; Maskrey 2011; Mercer 2010; Schipper and Pelling 2006; Sternberg and Batbuyan 2013; Thomalla et al. 2006; Vogel and O'Brien 2006
Risk-sharing instruments	Risk-sharing instruments can encompass a variety of approaches. Intra-household risk pooling is a common strategy in rural communities, such as through extended family financial transfers; one study found that 65% of poor households in Jamaica report receiving transfers, and such transfers can account for up to 75% of household income or more after crisis events. Community rotating savings and credit associations (ROSCAs) have long been used for general risk pooling and can be a source of financing to cope with climate variability as well. Credit services have been shown to be important for adaptation actions and risk reduction. Insurance of various kinds is also a form of risk pooling. Commercial crop insurance is one of the most widely used risk-hedging financial vehicles, and can involve both traditional indemnity-based insurance that reimburses clients for estimated financial losses from shortfalls, or index insurance that pays out the value of an index (such as weather events) rather than actual losses; the former is more common for large farms in the developed world and the latter for smaller non-commercial farms in developing countries.	Locally developed risk-pooling measures show general positive impacts on household livelihoods. However, more commercial approaches have mixed effects. Commercial crop insurance is highly subsidised in much of the developed world. Index insurance programmes have often failed to attract sufficient buyers or have remained financially unfeasible for commercial insurance sellers. The overall impact of index insurance on food production supply and access has also not been assessed. Traditional crop insurance has generally been seen as positive for food security as it leads to expansion of agricultural production areas and increased food supply. However, insurance may also 'mask' truly risky agriculture and prevent farmers from seeking less risky production strategies. Insurance can also provide perverse incentives for farmers to bring additional lands into crop production, leading to greater risk of degradation.	Akter et al. 2016; Annan and Schlenker 2015; Claassen et al. 2011a; Fenton et al. 2017; Giné et al. 2008; Goodwin and Smith 2003; Hammill et al. 2008; Havemenn and Muccione 2011; Jaworski 2016; Meze-Hausken et al. 2009; Morduch and Sharma 2002; Bhattamishra and Barrett 2010; Peterson 2012; Sanderson et al. 2013; Skees and Collier 2012; Smith and Glauber 2012

Cross-Chapter Box 7 | Bioenergy and bioenergy with carbon capture and storage (BECCS) in mitigation scenarios

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Bioenergy and BECCS potential

Using biomass to produce heat, electricity and transport fuels (bioenergy) instead of coal, oil, and natural gas can reduce GHG emissions. Combining biomass conversion technologies with systems that capture CO_2 and inject it into geological formations, BECCS can deliver net negative emissions. The net climate effects of bioenergy and BECCS depend on the magnitude of bioenergy supply chain emissions and land/climate interactions, described further below.

Cross-Chapter Box 7 (continued)

Biomass in 2013 contributed about 60 EJ (10%) to global primary energy[4] (WBA 2016). In 2011, the IPCC Special Report on Renewable Energy Sources concluded that biomass supply for energy could reach 100–300 EJ yr^{-1} by 2050 with the caveat that the technical potential[5] cannot be determined precisely while societal preferences are unclear; that deployment depends on 'factors that are inherently uncertain'; and that biomass use could evolve in a 'sustainable' or 'unsustainable' way, depending on the governance context (IPCC 2012). The IPCC WGIII AR5 report noted, in addition, that high deployment levels would require extensive use of technologies able to convert lignocellulosic biomass such as forest wood, agricultural residues, and lignocellulosic crops. The IPCC Special Report on Global Warming of 1.5°C (SR15) noted that high levels of bioenergy deployment may result in adverse side effects for food security, ecosystems, biodiversity, water use, and nutrients (de Coninck et al. 2018).

Although estimates of potential are uncertain, there is *high confidence* that the most important factors determining future biomass supply are land availability and land productivity. These factors are, in turn, determined by competing uses of land and a myriad of environmental and economic considerations (Dornburg et al. 2010; Batidzirai et al. 2012; Erb et al. 2012; Slade 2014, Searle and Malins 2014). Overlaying estimates of technical potential with such considerations invariably results in a smaller estimate. Recent studies that have attempted to do this estimate that 50–244 EJ biomass could be produced on 0.1–13 Mkm^2 (Fuss et al. 2018; Schueler et al. 2016; Searle and Malins 2014; IPCC 2018; Wu et al. 2019; Heck et al. 2018; de Coninck et al. 2018). While preferences concerning economic, social and environmental objectives vary geographically and over time, studies commonly estimate 'sustainable' potentials by introducing restrictions intended to protect environmental values and avoid negative effects on poor and vulnerable segments in societies.

Estimates of global geological CO_2 storage capacity are large – ranging from 1680 $GtCO_2$ to 24,000 $GtCO_2$ (McCollum et al. 2014) – however, the potential of BECCS may be significantly constrained by socio-political and technical and geographical considerations, including limits to knowledge and experience (Chapters 6 and 7).

Bioenergy and BECCS use in mitigation scenarios

Most mitigation scenarios include substantial deployment of bioenergy technologies (Clarke et al. 2014; Fuss et al. 2014; IPCC 2018). Across all scenarios, the amount of bioenergy and BECCS ranges from 0 EJ yr^{-1} to 561 EJ yr^{-1} in 2100 (Figure 1 in this box, left panel). Notably, all 1.5°C pathways include bioenergy, requiring as much as 7 Mkm^2 to be dedicated to the production of energy crops in 2050 (Rogelj et al. 2018a). If BECCS is excluded as a mitigation option, studies indicate that more biomass may be required in order to substitute for a greater proportion of fossil fuels (Muratori et al. 2016; Rose et al. 2014).

Different Integrated Assessment Models (IAMs) use alternative approaches to land allocation when determining where and how much biomass is used, with some relying on economic approaches and some relying on rule-based approaches (Popp et al. 2014). Despite these differences, a consistent finding across models is that increasing biomass supply to the extent necessary to support deep decarbonisation is likely to involve substantial land-use change (Popp et al. 2017) (Cross-Chapter Box 9 in this chapter). In model runs, bioenergy deployment and the consequent demand for biomass and land, is influenced by assumptions around the price of bioenergy, the yield of bioenergy crops, the cost of production (including the costs of fertiliser and irrigation if used), the demand for land for other uses, and the inclusion of policies (e.g., subsidies, taxes, constraints) that may alter land-use or bioenergy demand. In general, higher carbon prices result in greater bioenergy deployment (Cross-Chapter Box 7, Figure 1, right panel) and a larger percentage of BECCS. Other factors can also strongly influence bioenergy use, including the cost and availability of fossil fuels (Calvin et al. 2016a), socio-economics (Popp et al. 2017), and policy (Calvin et al. 2014; Reilly et al. 2012).

Co-benefits, adverse side effect, and risks associated with bioenergy

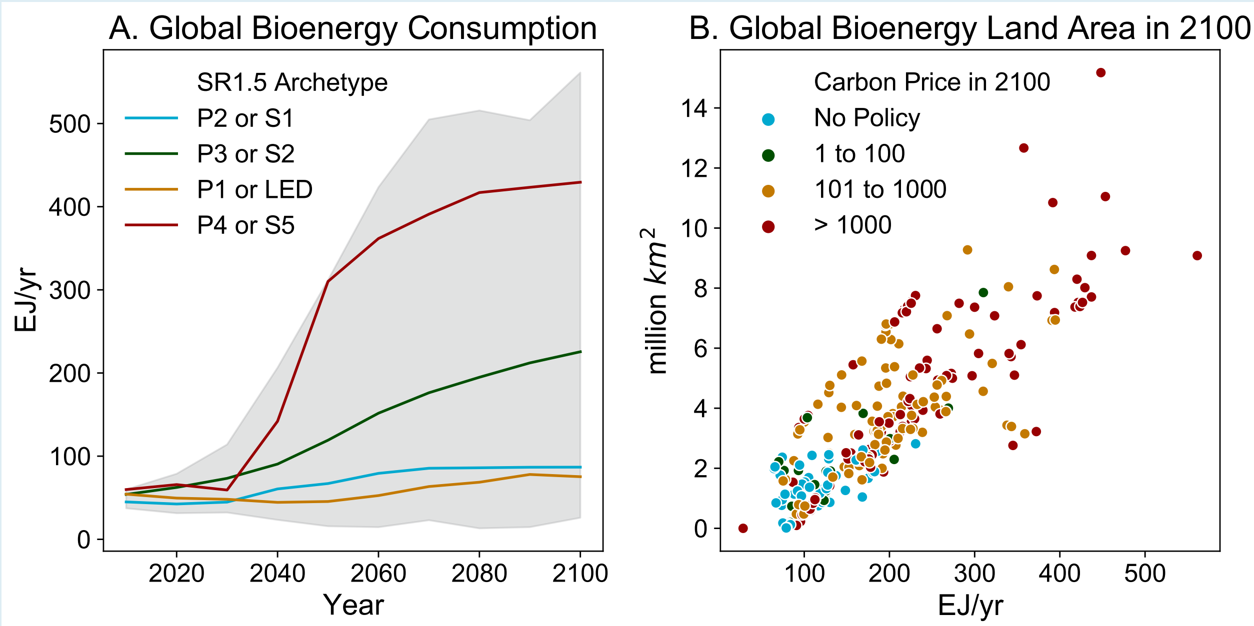
The production and use of biomass for bioenergy can have co-benefits, adverse side effects, and risks for land degradation, food insecurity, GHG emissions, and other environmental goals. These impacts are context specific and depend on the scale of deployment, initial land use, land type, bioenergy feedstock, initial carbon stocks, climatic region and management regime (Qin et al. 2016; Del Grosso et al. 2014; Alexander et al. 2015; Popp et al. 2017; Davis et al. 2013; Mello et al. 2014; Hudiburg et al. 2015; Carvalho et al. 2016; Silva-Olaya et al. 2017; Whitaker et al. 2018; Robledo-Abad et al. 2017; Jans et al. 2018).

6

[4] Of this, more than half was traditional biomass, predominately used for cooking and heating in developing regions, bioelectricity accounted for about 1.7 EJ, and transport biofuels for 3.19 EJ. (Cross-Chapter Box 12 in Chapter 7).

[5] The future availability of biomass is usually discussed in terms of a hierarchy of potentials: theoretical>technical>economic. Caution is required, however, as these terms are not always defined consistently and estimates depend on the specific definitions and calculation methodologies.

Cross-Chapter Box 7 (continued)



Cross-Chapter Box 7, Figure 1 | Global bioenergy consumption in IAM scenarios. Data is from an update of the Integrated Assessment Modelling Consortium (IAMC) Scenario Explorer developed for the SR15 (Huppmann et al. 2018; Rogelj et al. 2018a). The left panel **A.** shows bioenergy deployment over time for the entire scenario database (grey areas) and the four illustrative pathways from SR15 (Rogelj et al. 2018a). The right panel **B.** shows global land area for energy crops in 2100 versus total global bioenergy consumption in 2100; colours indicate the carbon price in 2100 (in 2010 USD per tCO_2). Note that this figure includes 409 scenarios, many of which exceed 1.5°C.

Synergistic outcomes with bioenergy are possible, for example, strategic integration of perennial bioenergy crops with conventional crops can provide multiple production and environmental benefits, including management of dryland salinity, enhanced biocontrol and biodiversity, and reduced eutrophication (Davis et al. 2013; Larsen et al. 2017; Cacho et al. 2018; Odgaard et al. 2019). Additionally, planting perennial bioenergy crops on low-carbon soil could enhance soil carbon sequestration (Bárcena et al. 2014; Schröder et al. 2018; Walter et al. 2015; Robertson et al. 2017a; Rowe et al. 2016; Chadwick et al. 2014; Immerzeel et al. 2014; Del Grosso et al. 2014; Mello et al. 2014; Whitaker et al. 2018). However, large-scale expansion of bioenergy may also result in increased competition for land (DeCicco 2013; Humpenöder et al. 2018; Bonsch et al. 2016; Harris et al. 2015; Richards et al. 2017; Ahlgren et al. 2017; Bárcena et al. 2014), increased GHG emissions from land-use change and land management, loss in biodiversity, and nutrient leakage (Harris et al. 2018; Harper et al. 2018; Popp et al. 2011b; Wiloso et al. 2016; Behrman et al. 2015; Valdez et al. 2017; Hof et al. 2018). If biomass crops are planted on land with a high carbon stock, the carbon loss due to land conversion may take decades to over a century to be compensated by either fossil fuel substitution or CCS (Harper et al. 2018). Competition for land may be experienced locally or regionally and is one of the determinants of food prices, food security (Popp et al. 2014; Bailey 2013; Pahl-Wostl et al. 2018; Rulli et al. 2016; Yamagata et al. 2018; Franz et al. 2017; Kline et al. 2017; Schröder et al. 2018) and water availability (Rulli et al. 2016; Bonsch et al. 2015; Pahl-Wostl et al. 2018; Bailey 2013; Chang et al. 2016; Bárcena et al. 2014).

Experience in countries at quite different levels of economic development (Brazil, Malawi and Sweden) has shown that persistent efforts over several decades to combine improved technical standards and management approaches with strong governance and coherent policies, can facilitate long-term investment in more sustainable production and sourcing of liquid biofuels (Johnson and Silveira 2014). For woody biomass, combining effective governance with active forest management over long time periods can enhance substitution-sequestration co-benefits, such as in Sweden where bioenergy has tripled during the last 40 years (currently providing about 25% of total energy supply) while forest carbon stocks have continued to grow (Lundmark et al. 2014). A variety of approaches are available at landscape level and in national and regional policies to better reconcile food security, bioenergy and ecosystem services, although more empirical evidence is needed (Mudombi et al. 2018; Manning et al. 2015; Kline et al. 2017; Maltsoglou et al. 2014; Lamers et al. 2016).

Thus, while there is *high confidence* that the technical potential for bioenergy and BECCS is large, there is also *very high confidence* that this potential is reduced when environmental, social and economic constraints are considered. The effects of bioenergy production on land degradation, water scarcity, biodiversity loss, and food insecurity are scale and context specific (*high confidence*). Large areas of monoculture bioenergy crops that displace other land uses can exacerbate these challenges, while integration into sustainably managed agricultural landscapes can ameliorate them (*medium confidence*).

Cross-Chapter Box 7 (continued)

Inventory reporting for BECCS and bioenergy

One of the complications in assessing the total GHG flux associated with bioenergy under United Nations Framework Convention on Climate Change (UNFCCC) reporting protocols is that fluxes from different aspects of bioenergy lifecycle are reported in different sectors and are not linked. In the energy sector, bioenergy is treated as carbon neutral at the point of biomass combustion because all change in land carbon stocks due to biomass harvest or land-use change related to bioenergy are reported under agriculture, forestry and other land-use (AFOLU) sector. Use of fertilisers is captured in the agriculture sector, while fluxes related to transport/conversion and removals due to CCS are reported in the energy sector. IAMs follow a similar reporting convention. Thus, the whole lifecycle GHG effects of bioenergy systems are not readily observed in national GHG inventories or modelled emissions estimates (see also IPCC 2006; SR15 Chapter 2 Technical Annex; Chapter 2).

Bioenergy in this report

Bioenergy and BECCS are discussed throughout this special report. Chapter 1 provides an introduction to bioenergy and BECCS and its links to land and climate. Chapter 2 discusses mitigation potential, land requirements and biophysical climate implications. Chapter 4 includes a discussion of the threats and opportunities with respect to land degradation. Chapter 5 discusses linkages between bioenergy and BECCS and food security. Chapter 6 synthesises the co-benefits and adverse side effects for mitigation, adaptation, desertification, land degradation, and food security, as well as barriers to implementation (e.g., cost, technological readiness, etc.). Chapter 7 includes a discussion of risk, policy, governance, and decision-making with respect to bioenergy and BECCS.

6.3 Potentials for addressing the land challenges

In this section, we assess how each of the integrated response options described in Section 6.2 address the land challenges of climate change mitigation (Section 6.3.1), climate change adaptation (Section 6.3.2), desertification (Section 6.3.3), land degradation (Section 6.3.4), and food security (Section 6.3.5). The quantified potentials across all of mitigation, adaptation, desertification, land degradation and food security are summarised and categorised for comparison in Section 6.3.6.

6.3.1 Potential of the integrated response options for delivering mitigation

In this section, the impacts of integrated response options on climate change mitigation are assessed.

6.3.1.1 Integrated response options based on land management

In this section, the impacts on climate change mitigation of integrated response options based on land management are assessed. Some of the caveats of these potential mitigation studies are discussed in Chapter 2 and Section 6.2.1.

Integrated response options based on land management in agriculture

Increasing the productivity of land used for food production can deliver significant mitigation by avoiding emissions that would occur if increased food demand were met through expansion of the agricultural land area (Burney et al. 2010). If pursued through increased agrochemical inputs, numerous adverse impacts on GHG emissions (and other environmental sustainability) can occur (Table 6.5), but, if pursued through sustainable intensification, increased food productivity could provide high levels of mitigation. For example, yield improvement has been estimated to have contributed to emissions savings of >13 $GtCO_2$ yr^{-1} since 1961 (Burney et al. 2010) (Table 6.13). This can also reduce the GHG intensity of products (Bennetzen et al. 2016a,b) which means a smaller environmental footprint of production, since demand can be met using less land and/or with fewer animals.

Improved cropland management could provide moderate levels of mitigation (1.4–2.3 $GtCO_2e$ yr^{-1}) (Smith et al. 2008, 2014; Pradhan et al. 2013) (Table 6.13). The lower estimate of potential is from Pradhan et al. (2013) for decreasing emissions intensity, and the upper end of technical potential is estimated by adding technical potentials for cropland management (about 1.4 $GtCO_2e$ yr^{-1}), rice management (about 0.2 $GtCO_2e$ yr^{-1}) and restoration of degraded land (about 0.7 $GtCO_2e$ yr^{-1}) from Smith et al. (2008) and Smith et al. (2014). Note that much of this potential arises from soil carbon sequestration so there is an overlap with that response option. (Section 6.3.1.1).

Grazing lands can store large stocks of carbon in soil and root biomass compartments (Conant and Paustian 2002; O'Mara 2012; Zhou et al. 2017). The global mitigation potential is moderate (1.4–1.8 $GtCO_2$ yr^{-1}), with the lower value in the range for technical potential taken from Smith et al. (2008) which includes only grassland management measures, and the upper value in the range from Herrero et al. (2016), which includes also indirect effects and some components of livestock management, and soil carbon sequestration, so there is overlap with these response options (Section 6.3.1.1).

6

Table 6.13 | Mitigation effects of response options based on land management in agriculture.

Integrated response option	Potential	Confidence	Citation
Increased food productivity	>13 $GtCO_2e\ yr^{-1}$	Low confidence	Chapter 5 Burney et al. 2010
Improved cropland management[a]	1.4–2.3 $GtCO_2e\ yr^{-1}$	Medium confidence	Chapter 2; Chapter 5 Pradhan et al. 2013; Smith et al. 2008, 2014
Improved grazing land management[a]	1.4–1.8 $GtCO_2e\ yr^{-1}$	Medium confidence	Chapter 2; Chapter 5 Conant et al. 2017; Herrero et al. 2016; Smith et al. 2008, 2014
Improved livestock management[a]	0.2–2.4 $GtCO_2e\ yr^{-1}$	Medium confidence	Chapter 2; Chapter 5 Herrero et al. 2016; Smith et al. 2008, 2014
Agroforestry	0.1–5.7 $GtCO_2e\ yr^{-1}$	Medium confidence	Chapter 2 Albrecht and Kandji 2003; Dickie et al. 2014; Griscom et al. 2017; Hawken 2017; Zomer et al. 2016
Agricultural diversification	>0	Low confidence	Campbell et al. 2014; Cohn et al. 2017
Reduced grassland conversion to cropland	0.03–0.7 $GtCO_2e\ yr^{-1}$	Low confidence	Note high value not shown in Chapter 2; calculated from values in Griscom et al. 2017; Krause et al. 2017; Poeplau et al. 2011
Integrated water management	0.1–0.72 $GtCO_2\ yr^{-1}$	Low confidence	IPCC 2014; Howell et al. 2015; Li et al. 2006; Rahman and Bulbul 2015; Smith et al. 2008, 2014

[a] Note that Chapter 2 reports mitigation potential for subcategories within this response option and not the combined total reported here.

Conant et al. (2005) caution that increases in soil carbon stocks could be offset by increases in N_2O fluxes.

The mitigation potential of improved livestock management is also moderate (0.2–1.8 $GtCO_2e\ yr^{-1}$; Smith et al. (2008) including only direct livestock measures; Herrero et al. (2016) include also indirect effects, and some components of grazing land management and soil carbon sequestration) to high (6.13 $GtCO_2e\ yr^{-1}$) (Pradhan et al. 2013) (Table 6.13). There is an overlap with other response options (Section 6.3.1.1).

Zomer et al. (2016) reported that the trees agroforestry landscapes have increased carbon stock by 7.33 $GtCO_2$ between 2000–2010, which is equivalent to 0.7 $GtCO_2\ yr^{-1}$. Estimates of global potential range from 0.1 $GtCO_2\ yr^{-1}$ to 5.7 $GtCO_2\ yr^{-1}$ (from an optimum implantation scenario of Hawken (2017), based on an assessment of all values in Griscom et al. (2017), Hawken (2017), Zomer et al. (2016) and Dickie et al. (2014) (Table 6.13).

Agricultural diversification mainly aims at increasing climate resilience, but it may have a small (but globally unquantified) mitigation potential as a function of type of crop, fertiliser management, tillage system, and soil type (Campbell et al. 2014; Cohn et al. 2017).

Reducing conversion of grassland to cropland could provide significant climate mitigation by retaining soil carbon stocks that might otherwise be lost. When grasslands are converted to croplands, they lose about 36% of their soil organic carbon stocks after 20 years (Poeplau et al. 2011). Assuming an average starting soil organic carbon stock of grasslands of 115 $tC\ ha^{-1}$ (Poeplau et al. 2011), this is equivalent to a loss of 41.5 $tC\ ha^{-1}$ on conversion to cropland. Mean annual global cropland conversion rates (1961–2003) have been around 47,000 $km^2\ yr^{-1}$ (Krause et al. 2017), or 940000 km^2 over a 20-year period. The equivalent loss of soil organic carbon over 20 years would therefore be 14 $GtCO_2e$ = 0.7 $GtCO_2\ yr^{-1}$. Griscom et al. (2017) estimate a cost-effective mitigation potential of 0.03 $GtCO_2\ yr^{-1}$ (Table 6.13).

Integrated water management provides moderate benefits for climate mitigation due to interactions with other land management strategies. For example, promoting soil carbon conservation (e.g., reduced tillage) can improve the water retention capacity of soils. Jat et al. (2015) found that improved tillage practices and residue incorporation increased water-use efficiency by 30%, rice–wheat yields by 5–37%, income by 28–40% and reduced GHG emission by 16–25%. While irrigated agriculture accounts for only 20% of the total cultivated land, the energy consumption from groundwater irrigation is significant. However, current estimates of mitigation potential are limited to reductions in GHG emissions mainly in cropland and rice cultivation (Smith et al. 2008, 2014) (Chapter 2 and Table 6.13). Li et al. (2006) estimated a 0.52–0.72 $GtCO_2\ yr^{-1}$ reduction using the alternate wetting and drying technique. Current estimates of N_2O release from terrestrial soils and wetlands accounts for 10–15% of anthropogenically fixed nitrogen on the Earth System (Wang et al. 2017).

Table 6.13 summarises the mitigation potentials for agricultural response options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.4.6, and indicative (not exhaustive) references upon which the evidence in based.

Integrated response options based on land management in forests

Forest management could potentially contribute to moderate mitigation benefits globally, up to about 2 $GtCO_2e\ yr^{-1}$ (Chapter 2, Table 6.14). For managed forests, the most effective forest carbon mitigation strategy is the one that, through increasing biomass productivity, optimises the carbon stocks (in forests and in long-lived products) as well as the wood substitution effects for a given time frame (Smyth et al. 2014; Grassi et al. 2018; Nabuurs et al. 2007; Lewis et al. 2019; Kurz et al. 2016; Erb et al. 2017). Estimates of the mitigation potential vary also depending on the counterfactual, such as business-as-usual management (e.g., Grassi et al. 2018) or other scenarios. Climate change will affect the mitigation potential of forest management due to an increase in extreme events like fires, insects and pathogens (Seidl et al. 2017). More detailed estimates are available at regional or biome level. For instance, according to Nabuurs et al. (2017), the implementation of Climate-Smart Forestry (a combination of forest management, expansion of forest areas, energy substitution, establishment of forest reserves, etc.) in the European Union has the potential to contribute to an additional 0.4 $GtCO_2$ yr^{-1} mitigation by 2050. Sustainable forest management is often associated with a number of co-benefits for adaptation, ecosystem services, biodiversity conservation, microclimatic regulation, soil erosion protection, coastal area protection and water and flood regulation (Locatelli 2011). Forest management mitigation measures are more likely to be long-lasting if integrated into adaptation measures for communities and ecosystems, for example, through landscape management (Locatelli et al. 2011). Adoption of reduced-impact logging and wood processing technologies along with financial incentives can reduce forest fires, forest degradation, maintain timber production, and retain carbon stocks (Sasaki et al. 2016). Forest certification may support sustainable forest management, helping to prevent forest degradation and over-logging (Rametsteiner and Simula 2003). Community forest management has proven a viable model for sustainable forestry, including for carbon sequestration (Chhatre and Agrawal 2009) (Chapter 7, Section 7.7.4).

Reducing deforestation and forest degradation rates represents one of the most effective and robust options for climate change mitigation, with large mitigation benefits globally (Chapters 2 and 4, and Table 6.14). Because of the combined climate impacts of GHGs and biophysical effects, reducing deforestation in the tropics has a major climate mitigation effect, with benefits at local levels too (Alkama and Cescatti 2016) (Chapter 2). Reduced deforestation and forest degradation typically lead to large co-benefits for other ecosystem services (Table 6.14).

A large range of estimates exist in the scientific literature for the mitigation potential of reforestation and forest restoration, and they sometimes overlap with estimates for afforestation. At global level, the overall potential for these options is large, reaching about 10 $GtCO_2$ yr^{-1} (Chapter 2 and Table 6.14). The greatest potential for these options is in tropical and subtropical climate (Houghton and Nassikas 2018). Furthermore, climate change mitigation benefits of afforestation, reforestation and forest restoration are reduced at high latitudes owing to the surface albedo feedback (Chapter 2).

Table 6.14 summarises the mitigation potentials for forest response options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.14 | Mitigation effects of response options based on land management in forests.

Integrated response option	Potential	Confidence	Citation
Forest management	0.4–2.1 $GtCO_2e$ yr^{-1}	Medium confidence	Chapter 2 Griscom et al. 2017; Sasaki et al. 2016
Reduced deforestation and forest degradation	0.4–5.8 $GtCO_2e$ yr^{-1}	High confidence	Chapter 2 Baccini et al. 2017; Griscom et al. 2017; Hawken 2017; Houghton et al. 2015; Houghton and Nassikas 2018; Smith et al. 2014
Reforestation and forest restoration	1.5–10.1 $GtCO_2e$ yr^{-1}	Medium confidence	Chapter 2 Dooley and Kartha 2018; Griscom et al. 2017; Hawken 2017; Houghton and Nassikas 2017 Estimates partially overlapping with Afforestation
Afforestation	0.5–8.9 $GtCO_2e$ yr^{-1}	Medium confidence	Chapter 2 Fuss et al. 2018; Hawken 2017; Kreidenweis et al. 2016; Lenton 2010. Estimates partially overlapping with Reforestation

Integrated response options based on land management of soils

The global mitigation potential for increasing soil organic matter stocks in mineral soils is estimated to be in the range of 1.3–5.1 $GtCO_2e$ yr^{-1}, though the full literature range is wider (Fuss et al. 2018; Lal 2004; de Coninck et al. 2018; Sanderman et al. 2017; Smith et al. 2008; Smith 2016) (Table 6.15).

The management and control of erosion may prevent losses of organic carbon in water- or wind- transported sediments, but since the final fate of eroded material is still debated, ranging from a source of 1.36–3.67 $GtCO_2$ yr^{-1} (Jacinthe and Lal 2001; Lal 2004) to a sink of 0.44–3.67 $GtCO_2$ yr^{-1} (Smith et al. 2001; Stallard 1998; Van Oost et al. 2007) (Table 6.15), the overall impact of erosion control on mitigation is context-specific and uncertain at the global level (Hoffmann et al. 2013).

Salt-affected soils are highly constrained environments that require permanent prevention of salinisation. Their mitigation potential is likely to be small (Wong et al. 2010; UNCTAD 2011; Dagar et al. 2016).

Soil compaction prevention could reduce N_2O emissions by minimising anoxic conditions favourable for denitrification (Mbow et al. 2010), but its carbon sequestration potential depends on crop management, and the global mitigation potential, though globally unquantified, is likely to be small (Chamen et al. 2015; Epron et al. 2016; Tullberg et al. 2018) (Table 6.15).

For biochar, a global analysis of technical potential, in which biomass supply constraints were applied to protect against food insecurity, loss of habitat and land degradation, estimated technical potential abatement of 3.7–6.6 $GtCO_2e$ yr^{-1} (including 2.6–4.6 $GtCO_2e$ yr^{-1} carbon stabilisation). Considering all published estimates by Woolf et al. (2010), Smith (2016), Fuss et al. (2018), Griscom et al. (2017), Hawken (2017), Paustian et al. (2016), Powell and Lenton (2012),

Table 6.15 | Mitigation effects of response options based on land management of soils.

Integrated response option	Potential	Confidence	Citation
Increased soil organic carbon content	0.4–8.6 $GtCO_2e\ yr^{-1}$	High confidence	Chapter 2 Conant et al. 2017; Dickie et al. 2014; Frank et al. 2017; Fuss et al. 2018; Griscom et al. 2017; Hawken 2017; Henderson et al. 2015; Herrero et al. 2016; Paustian et al. 2016; Powlson et al. 2014; Sanderman et al. 2017; Smith 2016; Smith et al. 2016b; Sommer and Bossio 2014; Zomer et al. 2016
Reduced soil erosion	Source of 1.36–3.67 to sink of 0.44–3.67 $GtCO_2e\ yr^{-1}$	Low confidence	Chapter 2 Jacinthe and Lal 2001; Lal 2004; Smith et al. 2001, 2005; Stallard 1998; Van Oost et al. 2007
Reduced soil salinisation	>0	Low confidence	Dagar et al. 2016; UNCTAD 2011; Wong et al. 2010
Reduced soil compaction	>0	Low confidence	Chamen et al. 2015; Epron et al. 2016; Tullberg et al. 2018
Biochar addition to soil	0.03–6.6 $GtCO_2e\ yr^{-1}$	Medium confidence	Chapter 2 Dickie et al. 2014; Fuss et al. 2018; Griscom et al. 2017; Hawken 2017; IPCC 2018; Lenton 2010, 2014; Paustian et al. 2016; Powell and Lenton 2012; Pratt and Moran 2010; Roberts et al. 2009; Smith 2016; Woolf et al. 2010

Dickie et al. (2014), Lenton (2010), Lenton (2014), Roberts et al. (2009), Pratt and Moran (2010) and IPCC (2018), the low value for the range of potentials of 0.03 $GtCO_2e\ yr^{-1}$ is for the 'plausible' scenario of Hawken, (2017) (Table 6.15). Fuss et al. (2018) propose a range of 0.5–2 $GtCO_2e\ yr^{-1}$ as the sustainable potential for negative emissions through biochar, similar to the range proposed by Smith (2016) and IPCC (2018).

Table 6.15 summarises the mitigation potentials for soil-based response options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Integrated response options based on land management in all/other ecosystems

For fire management, total emissions from fires have been in the order of 8.1 $GtCO_2e\ yr^{-1}$ for the period 1997–2016 (Chapter 2 and Cross-Chapter Box 3) and there are important synergies between air pollution and climate change control policies. Reduction in fire CO_2 emissions due to fire suppression and landscape fragmentation associated with increases in population density is calculated to enhance land carbon uptake by 0.48 $GtCO_2e\ yr^{-1}$ for the 1960–2009 period (Arora and Melton 2018) (Table 6.16).

Management of landslides and natural hazards is a key climate adaptation option but, due to limited global areas vulnerable to landslides and natural hazards, its mitigation potential is likely to be modest (Noble et al. 2014).

In terms of management of pollution, including acidification, United Nations Environment Programme (UNEP) and World Meterological Organization (WMO) (2011) and Shindell et al. (2012) identified measures targeting reduction in short-lived climate pollutant (SLCP) emissions that reduce projected global mean warming about 0.5°C by 2050. Bala et al. (2013) reported that a recent coupled modelling study showed nitrogen deposition and elevated CO_2 could have a synergistic effect, which could explain 47% of terrestrial carbon uptake in the 1990s. Estimates of global terrestrial carbon uptake due to current nitrogen deposition ranges between 0.55 and 1.28 $GtCO_2\ yr^{-1}$ (De Vries et al. 2006, 2009; Bala et al. 2013; Zaehle and Dalmonech 2011) (Table 6.16).

There are no global data on the impacts of management of invasive species/encroachment on mitigation.

Coastal wetland restoration could provide high levels of climate mitigation, with avoided coastal wetland impacts and coastal wetland restoration estimated to deliver 0.3–3.1 $GtCO_2e\ yr^{-1}$ in total when considering all global estimates from Griscom et al. (2017), Hawken (2017), Pendleton et al. (2012), Howard et al. (2017) and Donato et al. (2011) (Table 6.16).

Peatland restoration could provide moderate levels of climate mitigation, with avoided peat impacts and peat restoration estimated to deliver 0.6–2 $GtCO_2e\ yr^{-1}$ from all global estimates published in Griscom et al. (2017), Hawken (2017), Hooijer et al. (2010), Couwenberg et al. (2010) and Joosten and Couwenberg (2008), though there could be an increase in methane emissions after restoration (Jauhiainen et al. 2008) (Table 6.16).

Mitigation potential from biodiversity conservation varies depending on the type of intervention and specific context. Protected areas are estimated to store over 300 Gt carbon, roughly corresponding to 15% of terrestrial carbon stocks (Campbell et al. 2008; Kapos et al. 2008). At global level, the potential mitigation resulting from protection of these areas for the period 2005–2095 is, on average, about 0.9 $GtCO_2$-eq yr^{-1} relative to a reference scenario (Calvin et al. 2014). The potential effects on the carbon cycle of management of wild animal species are context dependent. For example, moose browsing in boreal forests can decrease the carbon uptake of ecosystems by up to 75% (Schmitz et al. 2018), and reducing moose density through active population management in Canada is estimated to be a carbon sink equivalent to about 0.37 $GtCO_2e\ yr^{-1}$ (Schmitz et al. 2014).

Table 6.16 summarises the mitigation potentials for land management response options in all/other ecosystems, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.16 | Mitigation effects of response options based on land management in all/other ecosystems.

Integrated response option	Potential	Confidence	Citation
Fire management	0.48–8.1 $GtCO_2e\ yr^{-1}$	Medium confidence	Chapter 2, Cross-Chapter Box 3 in Chapter 2 Arora and Melton 2018; Tacconi 2016
Reduced landslides and natural hazards	>0	Low confidence	
Reduced pollution including acidification	(i) Reduce projected warming ~0.5°C by 2050; (ii) Reduce terrestrial carbon uptake 0.55–1.28 $GtCO_2e\ yr^{-1}$	(i) and (ii) Medium confidence	(i) Shindell et al. 2012; UNEP and WMO 2011 (ii) Bala et al. 2013
Management of invasive species/encroachment	No global estimates	No evidence	
Restoration and reduced conversion of coastal wetlands	0.3–3.1 $GtCO_2e\ yr^{-1}$	Medium confidence	Chapter 2 Donato et al. 2011; Duarte et al. 2013; Hawken 2017; Howard et al. 2017; Pendleton et al. 2012
Restoration and reduced conversion of peatlands	0.6–2 $GtCO_2e\ yr^{-1}$	Medium confidence	Chapter 2 Couwenberg et al. 2010; Griscom et al. 2017; Hawken 2017; Hooijer et al. 2010; Joosten and Couwenberg 2008
Biodiversity conservation	~0.9 $GtCO_2e\ yr^{-1}$	Low confidence	Chapter 2 Calvin et al. 2014; Schmitz et al. 2014

Integrated response options based on land management specifically for carbon dioxide removal (CDR)

Enhanced mineral weathering provides substantial climate mitigation, with a global mitigation potential in the region of about 0.5–4 $GtCO_2e\ yr^{-1}$ (Beerling et al. 2018; Lenton 2010; Smith et al. 2016a; Taylor et al. 2016) (Table 6.17).

The mitigation potential for bioenergy and BECCS derived from bottom-up models is large (IPCC 2018) (Chapter 2 and Cross-Chapter Box 7 in this chapter), with technical potential estimated at 100–300 EJ yr^{-1} (Chum et al. 2011; Cross-Chapter Box 7 in Chapter 6) or up to about 11 $GtCO_2\ yr^{-1}$ (Chapter 2). These estimates, however, exclude N_2O associated with fertiliser application and land-use change emissions. Those effects are included in the modelled scenarios using bioenergy and BECCS, with the sign and magnitude depending on where the bioenergy is grown (Wise et al. 2015), at what scale, and whether nitrogen fertiliser is used.

Table 6.17 summarises the mitigation potentials for land management options specifically for CDR, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.17 | Mitigation effects of response options based on land management specifically for CDR.

Integrated response option	Potential	Confidence	Citation
Enhanced weathering of minerals	0.5–4 $GtCO_2\ yr^{-1}$	Medium confidence	Chapter 2 Beerling et al. 2018; Lenton 2010; Smith et al. 2016a; Taylor et al. 2016
Bioenergy and BECCS	0.4–11.3 $GtCO_2\ yr^{-1}$	Medium confidence	Chapter 2 IPCC 2018; Fuss et al. 2018; McLaren 2012; Lenton 2010, 2014; Powell and Lenton 2012

6.3.1.2 Integrated response options based on value chain management

In this section, the impacts on climate change mitigation of integrated response options based on value chain management are assessed.

Integrated response options based on value chain management through demand management

Dietary change and waste reduction can provide large benefits for mitigation, with potentials of 0.7–8 $GtCO_2\ yr^{-1}$ for both (Aleksandrowicz et al. 2016; Bajželj et al. 2014b; Dickie et al. 2014; Hawken 2017; Hedenus et al. 2014; Herrero et al. 2016; Popp et al. 2010; Smith et al. 2013; Springmann et al. 2016; Stehfest et al. 2009; Tilman and Clark 2014). Estimates for food waste reduction (Bajželj et al. 2014b; Dickie et al. 2014; Hiç et al. 2016; Hawken 2017) include both consumer/retailed waste and post-harvest losses (Table 6.18).

Some studies indicate that material substitution has the potential for significant mitigation, with one study estimating a 14–31% reduction in global CO_2 emissions (Oliver et al. 2014); other studies suggest more modest potential (Gustavsson et al. 2006) (Table 6.18).

Table 6.18 summarises the mitigation potentials for demand management options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.18 | Mitigation effects of response options based on demand management.

Integrated response option	Potential	Confidence	Citation
Dietary change	0.7–8 $GtCO_2\ yr^{-1}$	High confidence	Chapter 2; Chapter 5 Aleksandrowicz et al. 2016; Bajželj et al. 2014b; Dickie et al. 2014; Hawken 2017; Hedenus et al. 2014; Herrero et al. 2016; Popp et al. 2010; Smith et al. 2013; Springmann et al. 2016; Stehfest et al. 2009; Tilman and Clark 2014
Reduced post-harvest losses	4.5 $GtCO_2\ yr^{-1}$	High confidence	Chapter 5 Bajželj et al. 2014b
Reduced food waste (consumer or retailer)	0.8–4.5 $GtCO_2\ yr^{-1}$	High confidence	Chapter 5 Bajželj et al. 2014b; Dickie et al. 2014; Hiç et al. 2016; Hawken 2017
Material substitution	0.25–1 $GtCO_2\ yr^{-1}$	Medium confidence	Chapter 2 Dugan et al. 2018; Gustavsson et al. 2006; Kauppi et al. 2001; Leskinen et al. 2018; McLaren 2012; Miner 2010; Sathre and O'Connor 2010; Smyth et al. 2017

Integrated response options based on value chain management through supply management

While sustainable sourcing presumably delivers a mitigation benefit, there are no global estimates of potential. Palm oil production alone is estimated to contribute 0.038 to 0.045 GtC yr^{-1}, and Indonesian palm oil expansion contributed up to 9% of tropical land-use change carbon emissions in the 2000s (Carlson and Curran 2013), however, the mitigation benefit of sustainable sourcing of palm oil has not been quantified. There are no estimates of the mitigation potential for urban food systems.

Efficient use of energy and resources in food transport and distribution contribute to a reduction in GHG emissions, estimated to be 1% of global CO_2 emissions (James and James 2010; Vermeulen et al. 2012b). Given that global CO_2 emissions in 2017 were 37 $GtCO_2$, this equates to 0.37 $GtCO_2\ yr^{-1}$ (covering food transport and distribution, improved efficiency of food processing and retailing, and improved energy efficiency) (Table 6.19).

Table 6.19 summarises the mitigation potentials for supply management options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.19 | Mitigation effects of response options based on supply management.

Integrated response option	Potential	Confidence	Citation
Sustainable sourcing	No global estimates	No evidence	
Management of supply chains	No global estimates	No evidence	
Enhanced urban food systems	No global estimates	No evidence	
Improved food processing and retailing	See improved energy efficiency		
Improved energy use in food systems	0.37 $GtCO_2\ yr^{-1}$	Low confidence	James and James 2010; Vermeulen et al. 2012b

6.3.1.3 Integrated response options based on risk management

In this section, the impacts on climate change mitigation of integrated response options based on risk management are assessed. In general, because these options are focused on adaptation and other benefits, the mitigation benefits are modest, and mostly unquantified.

Extensive and less dense urban development tends to have higher energy usage, particularly from transport (Liu et al. 2015), such that a 10% reduction of very low-density urban fabrics is correlated with 9% fewer emissions per capita in Europe (Baur et al. 2015). However, the exact contribution to mitigation from the prevention of land conversion in particular has not been well quantified (Thornbush et al. 2013). Suggestions from select studies in the USA are that biomass decreases by half in cases of conversion from forest to urban land uses (Briber et al. 2015), and a study in Bangkok found a decline by half in carbon sinks in the urban area in the past 30 years (Ali et al. 2018).

There is no literature specifically on linkages between livelihood diversification and climate mitigation benefits, although some forms of diversification that include agroforestry would likely result in increased carbon sinks (Altieri et al. 2015; Descheemaeker et al. 2016). There is no literature exploring linkages between local seeds and GHG emission reductions, although use of local seeds likely reduces emissions associated with transport for commercial seeds, though the impact has not been quantified.

While disaster risk management can presumably have mitigation co-benefits, as it can help reduce food loss on-farm (e.g., crops destroyed before harvest or avoided animal deaths during droughts and floods meaning reduced production losses and wasted emissions), there is no quantified global estimate for this potential.

Risk-sharing instruments could have some mitigation co-benefits if they buffer household losses and reduce the need to expand agricultural lands after experiencing risks. However, the overall impacts of these are unknown. Further, commercial insurance may induce producers to bring additional land into crop production, particularly marginal or land with other risks that may be more environmentally sensitive (Claassen et al. 2011a). Policies to deny crop insurance to farmers who have converted grasslands in the USA resulted in a 9% drop in conversion, which likely has positive mitigation impacts (Claassen et al. 2011a). Estimates of emissions from cropland conversion in the USA in 2016 were 23.8 $MtCO_2e$, only some of which could be attributed to insurance as a driver.

Table 6.20 summarises the mitigation potentials for risk management options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence is based.

Table 6.20 | Mitigation effects of response options based on risk management.

Integrated response option	Potential	Confidence	Citation
Management of urban sprawl	No global estimates	No evidence	
Livelihood diversification	No global estimates	No evidence	
Use of local seeds	No global estimates	No evidence	
Disaster risk management	No global estimates	No evidence	
Risk-sharing instruments	>0.024 $GtCO_2e\ yr^{-1}$ for crop insurance; likely some benefits for other risk-sharing instruments	Low confidence	Claassen et al. 2011b; EPA 2018

6.3.2 Potential of the integrated response options for delivering adaptation

In this section, the impacts of integrated response options on climate change adaptation are assessed.

6.3.2.1 Integrated response options based on land management

In this section, the impacts on climate change adaptation of integrated response options based on land management are assessed.

Integrated response options based on land management in agriculture

Increasing food productivity by practices such as sustainable intensification improves farm incomes and allows households to build assets for use in times of stress, thereby improving resilience (Campbell et al. 2014). By reducing pressure on land and increasing food production, increased food productivity could be beneficial for adaptation (Campbell et al. 2014) (Chapter 2 and Section 6.3). Pretty et al. (2018) report that 163 million farms occupying 4.53 Mkm^2 have passed a redesign threshold for application of sustainable intensification, suggesting the minimum number of people benefitting from increased productivity and adaptation benefits under sustainable intensification is >163 million, with the total likely to be far higher (Table 6.21).

Improved cropland management is a key climate adaptation option, potentially affecting more than 25 million people, including a wide range of technological decisions by farmers. Actions towards adaptation fall into two broad overlapping areas: (i) accelerated adaptation to progressive climate change over decadal time scales, for example integrated packages of technology, agronomy and policy options for farmers and food systems, including changing planting dates and zones, tillage systems, crop types and varieties, and (ii) better management of agricultural risks associated with increasing climate variability and extreme events, for example, improved climate information services and safety nets (Vermeulen et al. 2012b; Challinor et al. 2014; Lipper et al. 2014; Lobell 2014). In the same way, improved livestock management is another technological adaptation option potentially benefitting between 1 million and 25 million people. Crop and animal diversification are considered the most promising adaptation measures (Porter et al. 2014; Rojas-Downing et al. 2017). In grasslands and rangelands, regulation of stocking rates, grazing field dimensions, establishment of exclosures and locations of drinking fountains and feeders are strategic decisions by farmers to improve grazing management (Taboada et al. 2011; Mekuria and Aynekulu 2013; Porter et al. 2014).

Around 30% of the world's rural population use trees across 46% of all agricultural landscapes (Lasco et al. 2014), meaning that up to 2.3 billion people benefit from agroforestry globally (Table 6.21).

Agricultural diversification is key to achieving climatic resilience (Campbell et al. 2014; Cohn et al. 2017). Crop diversification is one important adaptation option to progressive climate change (Vermeulen et al. 2012a) and it can improve resilience by engendering a greater ability to suppress pest outbreaks and dampen pathogen transmission, as well as by buffering crop production from the effects of greater climate variability and extreme events (Lin 2011).

Reduced conversion of grassland to cropland may lead to adaptation benefits by stabilising soils in the face of extreme climatic events (Lal 2001), thereby increasing resilience, but since it would likely have a negative impact on food production/security (since croplands produce more food per unit area than grasslands), the wider adaptation impacts would likely be negative. However, there is no literature quantifying the global impact of avoidance of conversion of grassland to cropland on adaptation.

Integrated water management provides large co-benefits for adaptation (Dillon and Arshad 2016) by improving the resilience of food crop production systems to future climate change (Porter et al. 2014) (Chapter 2 and Table 6.7). Improving irrigation systems and integrated water resource management, such as enhancing urban and rural water supplies and reducing water evaporation losses (Dillon and Arshad 2016), are significant options for enhancing climate adaptation. Many technical innovations (e.g., precision water management) can lead to beneficial adaptation outcomes by increasing water availability and the reliability of agricultural production, using different techniques of water harvesting, storage, and its judicious utilisation through farm ponds, dams and community tanks in rainfed agriculture areas. Integrated water management response options that use freshwater would be expected to have few adverse side effects in regions where water is plentiful, but large adverse side effects in regions where water is scarce (Grey and Sadoff 2007; Liu et al. 2017; Scott et al. 2011).

Table 6.21 summarises the potentials for adaptation for agricultural response options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.21 | Adaptation effects of response options based on land management in agriculture.

Integrated response option	Potential	Confidence	Citation
Increased food productivity	>163 million people	Medium confidence	Pretty et al. 2018
Improved cropland management	>25 million people	Low confidence	Challinor et al. 2014; Lipper et al. 2014; Lobell 2014; Vermeulen et al. 2012b
Improved grazing land management	1–25 million people	Low confidence	Porter et al. 2014
Improved livestock management	1–25 million people	Low confidence	Porter et al. 2014; Rojas-Downing et al. 2017
Agroforestry	2300 million people	Medium confidence	Lasco et al. 2014
Agricultural diversification	>25 million people	Low confidence	Campbell et al. 2014; Cohn et al. 2017; Vermeulen et al. 2012b
Reduced grassland conversion to cropland	No global estimates	No evidence	
Integrated water management	250 million people	Low confidence	Dillon and Arshad 2016; Liu et al. 2017

Integrated response options based on land management in forestry

Forest management positively impacts on adaptation through limiting the negative effects associated with pollution (of air and fresh water), infections and other diseases, exposure to extreme weather events and natural disasters, and poverty (e.g., Smith et al. 2014). There is high agreement on the fact that reduced deforestation and forest degradation positively impact on adaptation and resilience of coupled human-natural systems. Based on the number of people affected by natural disasters (CRED 2015), the number of people depending to varying degrees on forests for their livelihoods (World Bank et al. 2009) and the current deforestation rate (Keenan et al. 2015), the estimated global potential effect for adaptation is largely positive for forest management, and moderately positive for reduced deforestation when cumulated until the end of the century (Table 6.22). The uncertainty of these global estimates is high, for example, the impact of reduced deforestation may be higher when the large biophysical impacts on the water cycle (and thus drought) from deforestation (e.g., Alkama and Cescatti 2016) are taken into account (Chapter 2).

More robust qualitative, and some quantitative, estimates are available at local and regional level. According to Karjalainen et al. (2009), reducing deforestation and habitat alteration contributes to limiting infectious diseases such as malaria in Africa, Asia and Latin America, thus lowering the expenses associated with healthcare treatments. Bhattacharjee and Behera (2017) found that human lives lost due to floods increase with reducing forest cover and increasing deforestation rates in India. In addition, maintaining forest cover in urban contexts reduces air pollution and therefore avoids mortality of about one person per year per city in US, and up to 7.6 people per year in New York City (Nowak et al. 2014). There is also evidence that reducing deforestation and forest degradation in mangrove plantations potentially improves soil stabilisation, and attenuates the impact of tropical cyclones and typhoons along the coastal areas in South and Southeast Asia (Chow 2018). At local scale, co-benefits between REDD+ and adaptation of local communities can potentially be substantial (Long 2013; Morita and Matsumoto 2018), even if often difficult to quantify, and not explicitly acknowledged (McElwee et al. 2017b).

Forest restoration may facilitate the adaptation and resilience of forests to climate change by enhancing connectivity between forest areas and conserving biodiversity hotspots (Locatelli et al. 2011, 2015b; Ellison et al. 2017; Dooley and Kartha 2018). Furthermore, forest restoration may improve ecosystem functionality and services, provide microclimatic regulation for people and crops, wood and fodder as safety nets, soil erosion protection and soil fertility enhancement for agricultural resilience, coastal area protection, water and flood regulation (Locatelli et al. 2015b).

Afforestation and reforestation are important climate change adaptation response options (Reyer et al. 2009; Ellison et al. 2017; Locatelli et al. 2015b), and can potentially help a large proportion of the global population to adapt to climate change and to associated natural disasters (Table 6.22). For example, trees generally mitigate summer mean warming and temperature extremes (Findell et al. 2017; Sonntag et al. 2016).

Table 6.22 summarises the potentials for adaptation for forest response options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

6

Table 6.22 | Adaptation effects of response options based on land management in forests.

Integrated response option	Potential	Confidence	Citation
Forest management	>25 million people	Low confidence	CRED 2015; World Bank et al. 2009
Reduced deforestation and forest degradation	1–25 million people	Low confidence	CRED 2015; Keenan et al. 2015; World Bank et al. 2009. The estimates consider a cumulated effect until the end of the century.
Reforestation and forest restoration	See afforestation		
Afforestation	>25 million people	Medium confidence	CRED 2015; Reyer et al. 2009; Smith et al. 2014; Sonntag et al. 2016; World Bank et al. 2009. The estimates consider a cumulated effect until the end of the century.

Integrated response options based on land management of soils

Soil organic carbon increase is promoted as an action for climate change adaptation. Since increasing soil organic matter content is a measure to address land degradation (see Section 6.2.1), and restoring degraded land helps to improve resilience to climate change, soil carbon increase is an important option for climate change adaptation. With around 120,000 km^2 lost to degradation every year, and over 3.2 billion people negatively impacted by land degradation globally (IPBES 2018), practices designed to increase soil organic carbon have a large potential to address adaptation challenges (Table 6.23).

Since soil erosion control prevents land degradation and desertification, it improves the resilience of agriculture to climate change and increases food production (Lal 1998; IPBES 2018), though the global number of people benefitting from improved resilience to climate change has not been reported in the literature. Using figures from (FAO and ITPS 2015), IPBES (2018) estimates that land losses due to erosion are equivalent to 1.5 Mkm^2 of land used for crop production to 2050, or 45,000 km^2 yr^{-1} (Foley et al. 2011). Control of soil erosion (water and wind) could benefit 11 Mkm^2 of degraded land (Lal 2014), and improve the resilience of at least some of the 3.2 billion people affected by land degradation (IPBES 2018), suggesting positive impacts on adaptation. Management of erosion is an important climate change adaptation measure, since it reduces the vulnerability of soils to loss under climate extremes, thereby increasing resilience to climate change (Garbrecht et al. 2015).

Prevention and/or reversion of topsoil salinisation may require a combined management of groundwater, irrigation techniques, drainage, mulching and vegetation, with all of these considered relevant for adaptation (Qadir et al. 2013; UNCTAD 2011; Dagar et al. 2016). Taking into account the widespread diffusion of salinity problems, many people can benefit from its implementation by farmers. The relation between compaction prevention and/or reversion and climate adaption is less evident, and can be related to better hydrological soil functioning (Chamen et al. 2015; Epron et al. 2016; Tullberg et al. 2018).

Biochar has the potential to benefit climate adaptation by improving the resilience of food crop production systems to future climate change by increasing yield in some regions and improving water holding capacity (Woolf et al. 2010; Sohi 2012) (Chapter 2 and Section 6.4). By increasing yield by 25% in the tropics (Jeffery et al. 2017), this could increase food production for 3.2 billion people affected by land degradation (IPBES 2018), thereby potentially improving their resilience to climate change shocks (Table 6.23). A requirement for large areas of land to provide feedstock for biochar could adversely impact on adaptation, though this has not been quantified globally.

Table 6.23 summarises the potentials for adaptation for soil-based response options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.23 | Adaptation effects of response options based on land management of soils.

Integrated response option	Potential	Confidence	Citation
Increased soil organic carbon content	Up to 3200 million people	Low confidence	IPBES 2018
Reduced soil erosion	Up to 3200 million people	Low confidence	IPBES 2018
Reduced soil salinisation	1–25 million people	Low confidence	Dagar et al. 2016; Qadir et al. 2013; UNCTAD 2011
Reduced soil compaction	<1 million people	Low confidence	Chamen et al. 2015; Epron et al. 2016; Tullberg et al. 2018
Biochar addition to soil	Up to 3200 million people; but potential negative (unquantified) impacts from land required from feedstocks	Low confidence	Jeffery et al. 2017

Integrated response options based on land management across all/other ecosystems

For fire management, Doerr et al. (2016) showed that the number of people killed by wildfire was 1940, and the total number of people affected was 5.8 million from 1984 to 2013, globally. Johnston et al. (2012) showed that the average mortality attributable to landscape fire smoke exposure was 339,000 deaths annually. The regions most affected were sub-Saharan Africa (157,000) and Southeast Asia (110,000). Estimated annual mortality during La Niña was 262,000, compared with around 100,000 excess deaths across Indonesia, Malaysia and Singapore (Table 6.24).

Management of landslides and natural hazards are usually listed among planned adaptation options in mountainous and sloped hilly areas, where uncontrolled runoff and avalanches may cause climatic disasters, affecting millions of people from both urban and rural areas. Landslide control requires increasing plant cover and engineering practices (see Table 6.8).

For management of pollution, including acidification, Anenberg et al. (2012) estimated that, for particulate matter ($PM_{2.5}$) and ozone, respectively, fully implementing reduction measures could reduce global population-weighted average surface concentrations by 23–34% and 7–17% and avoid 0.6–4.4 and 0.04–0.52 million annual premature deaths globally in 2030. UNEP and WMO (2011) considered emission control measures to reduce ozone and black carbon (BC) and estimated that 2.4 million annual premature deaths (with a range of 0.7 million to 4.6 million) from outdoor air pollution could be avoided. West et al. (2013) estimated global GHG mitigation brings co-benefits for air quality and would avoid 0.5 ± 0.2, 1.3 ± 0.5, and 2.2 ± 0.8 million premature deaths in 2030, 2050, and 2100, respectively.

There are no global data on the impacts of management of invasive species/encroachment on adaptation.

Coastal wetlands provide a natural defence against coastal flooding and storm surges by dissipating wave energy, reducing erosion, and by helping to stabilise shore sediments, so restoration may provide significant benefits for adaptation. The Ramsar Convention on Wetlands covers 1.5 Mkm^2 across 1674 sites (Keddy et al. 2009). Coastal floods currently affect 93–310 million people (in 2010) globally, and this could rise to 600 million people in 2100 with sea level rise, unless adaptation measures are taken (Hinkel et al. 2014). The proportion of the flood-prone population that could avoid these impacts through restoration of coastal wetlands has not been quantified, but this sets an upper limit.

Avoided peat impacts and peatland restoration can help to regulate water flow and prevent downstream flooding (Munang et al. 2014), but the global potential (in terms of number of people who could avoid flooding through peatland restoration) has not been quantified.

There are no global estimates about the potential of biodiversity conservation to improve the adaptation and resilience of local communities to climate change, in terms of reducing the number of people affected by natural disasters. Nevertheless, it is widely recognised that biodiversity, ecosystem health and resilience improves the adaptation potential (Jones et al. 2012). For example, tree species mixture improves the resistance of stands to natural disturbances, such as drought, fires, and windstorms (Jactel et al. 2017), as well as stability against landslides (Kobayashi and Mori 2017). Moreover, protected areas play a key role for improving adaptation (Watson et al. 2014; Lopoukhine et al. 2012), through reducing water flow, stabilising rock movements, creating physical barriers to coastal erosion, improving resistance to fires, and buffering storm damages (Dudley et al. 2010). Of the largest urban areas worldwide, 33 out of 105 rely on protected areas for some, or all, of their drinking water (Secretariat of the Convention on Biological Diversity 2008), indicating that many millions are likely to benefit from conservation practices.

Table 6.24 summarises the potentials for adaptation for soil-based response options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.24 | Adaptation effects of response options based on land management of soils.

Integrated response option	Potential	Confidence	Citation
Fire management	>5.8 million people affected by wildfire; max. 0.5 million deaths per year by smoke	Medium confidence	Doerr and Santín 2016; Johnston et al. 2012; Koplitz et al. 2016
Reduced landslides and natural hazards	>25 million people	Low confidence	Arnáez J et al. 2015; Gariano and Guzzetti 2016
Reduced pollution including acidification	Prevent 0.5–4.6 million annual premature deaths globally	Medium confidence	Anenberg et al. 2012; Shindell et al. 2012; West et al. 2013; UNEP and WMO 2011
Management of invasive species/encroachment	No global estimates	No evidence	
Restoration and reduced conversion of coastal wetlands	Up to 93–310 million people	Low confidence	Hinkel et al. 2014
Restoration and reduced conversion of peatlands	No global estimates	No evidence	
Biodiversity conservation	Likely many millions	Low confidence	Secretariat of the Convention on Biological Diversity 2008

Integrated response options based on land management specifically for CDR

Enhanced weathering of minerals has been proposed as a mechanism for improving soil health and food security (Beerling et al. 2018), but there is no literature estimating the global adaptation benefits.

Large-scale bioenergy and BECCS can require substantial amounts of cropland (Popp et al. 2017; Calvin et al. 2014; Smith et al. 2016a), forestland (Baker et al. 2019; Favero and Mendelsohn 2017), and water (Chaturvedi et al. 2013; Hejazi et al. 2015; Popp et al. 2011a; Smith et al. 2016a; Fuss et al. 2018); suggesting that bioenergy and BECCS could have adverse side effects for adaptation. In some contexts – for example, low inputs of fossil fuels and chemicals, limited irrigation, heat/drought tolerant species, and using marginal land – bioenergy can have co-benefits for adaptation (Dasgupta et al. 2014; Noble et al. 2014). However, no studies were found that quantify the magnitude of the effect.

Table 6.25 summarises the impacts on adaptation of land management response options specifically for CDR, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.25 | Adaptation effects of response options based on land management specifically for CDR.

Integrated response option	Potential	Confidence	Citation
Enhanced weathering of minerals	No global estimates	No evidence	
Bioenergy and BECCS	Potentially large negative consequences	Low confidence	Fuss et al. 2018; Muller et al. 2017; Smith et al. 2016a

6.3.2.2 Integrated response options based on value chain management

In this section, the impacts on climate change adaptation of integrated response options based on value chain management are assessed.

Integrated response options based on value chain management through demand management

Decreases in pressure on land and decreases in production intensity associated with sustainable healthy diets or reduced food waste could also benefit adaptation; however, the size of this effect is not well quantified (Muller et al. 2017).

Reducing food waste losses can relieve pressure on the global freshwater resource, thereby aiding adaptation. Food losses account for 215 $km^3 yr^{-1}$ of freshwater resources, which Kummu et al. (2012) report to be about 12–15% of the global consumptive water use. Given that 35% of the global population is living under high water stress or shortage (Kummu et al. 2010), reducing food waste could benefit 320–400 million people (12–15% of the 2681 million people affected by water stress/shortage).

While no studies report quantitative estimates of the effect of material substitution on adaptation, the effects are expected to be similar to reforestation and afforestation if the amount of material substitution leads to an increase in forest area. Additionally, some studies indicate that wooden buildings, if properly constructed, could reduce fire risk, compared to steel, which softens when burned (Gustavsson et al. 2006; Ramage et al. 2017).

Table 6.26 summarises the impacts on adaptation of demand management options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.26 | Adaptation effects of response options based on demand management.

Integrated response option	Potential	Confidence	Citation
Dietary change	No global estimates	No evidence	Muller et al. 2017
Reduced post-harvest losses	320–400 million people	Medium confidence	Kummu et al. 2012
Reduced food waste (consumer or retailer)	No global estimates	No evidence	Muller et al. 2017
Material substitution	No global estimates	No evidence	

Integrated response options based on value chain management through supply management

It is estimated that 500 million smallholder farmers depend on agricultural businesses in developing countries (IFAD 2013), meaning that better promotion of value-added products and improved efficiency and sustainability of food processing and retailing could potentially help up to 500 million people to adapt to climate change. However, figures on how sustainable sourcing in general could help farmers and forest management is mostly unquantified. More than 1 million farmers have currently been certified through various schemes (Tayleur et al. 2017), but how much this has helped them prepare for adaptation is unknown.

Management of supply chains has the potential to reduce vulnerability to price volatility. Consumers in lower-income countries are most affected by price volatility, with sub-Saharan Africa and South Asia at highest risk (Regmi and Meade 2013; Fujimori et al. 2019). However, understanding of the stability of food supply is one of the weakest links in global food system research (Wheeler and von Braun 2013) as instability is driven by a confluence of factors (Headey and Fan 2008). Food price spikes in 2007 increased the number of people below the poverty line by between 100 million people (Ivanic and Martin 2008) and 450 million people (Brinkman et al. 2009), and caused welfare losses of 3% or more for poor households in many countries (Zezza et al. 2009). Food price stabilisation by China, India and Indonesia alone in 2007/2008 led to reduced staple food price for 2 billion people (Timmer 2009). Presumably, spending less on food frees up money for other activities, including adaptation, but it is unknown how much (Zezza et al. 2009; Ziervogel and Ericksen 2010). In one example, reduction in staple food price costs to consumers in Bangladesh from food stability policies saved rural households 887 million USD2003 total (Torlesse et al. 2003). Food supply stability through improved supply chains also potentially reduces conflicts (by avoiding food price riots, which occurred in countries with over 100 million total in population in 2007/2008), and thus increases adaptation capacity (Raleigh et al. 2015).

There are no global estimates of the contribution of improved food transport and distribution, or of urban food systems, in contributing to adaptation, but since the urban population in 2018 was 4.2 billion people, this sets the upper limit on those who could benefit.

Given that 65% (760 million) of working adults in poverty make a living through agriculture, increased energy efficiency in agriculture could benefit these 760 million people.

Table 6.27 summarises the impacts on adaptation of supply management options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.27 | Adaptation effects of response options based on demand management.

Integrated response option	Potential	Confidence	Citation
Sustainable sourcing	>1 million	Low confidence	Tayleur et al. 2017
Management of supply chains	>100 million	Medium confidence	Campbell et al. 2016; Ivanic and Martin 2008; Timmer 2009; Vermeulen et al. 2012b
Enhanced urban food systems	No global estimates	No evidence	
Improved food processing and retailing	500 million people	Low confidence	IFAD 2013; World Bank 2017
Improved energy use in food systems	760 million	Low confidence	IFAD 2013; World Bank 2017

6.3.2.3 Integrated response options based on risk management

In this section, the impacts on climate change adaptation of integrated response options based on risk management are assessed.

Reducing urban sprawl is likely to provide adaptation co-benefits *via* improved human health (Frumkin 2002; Anderson 2017), as sprawl contributes to reduced physical activity, worse air pollution, and exacerbation of urban heat island effects and extreme heat waves (Stone et al. 2010). The most sprawling cities in the US have experienced extreme heat waves, more than double those of denser cities, and 'urban albedo and vegetation enhancement strategies have significant potential to reduce heat-related health impacts' (Stone et al. 2010). Other adaption co-benefits are less well understood. There are likely to be cost savings from managing planning growth (one study found 2% savings in metropolitan budgets, which can then be spent on adaptation planning) (Deal and Schunk 2004).

Diversification is a major adaptation strategy and form of risk management, as it can help households smooth out income fluctuations and provide a broader range of options for the future (Osbahr et al. 2008; Adger et al. 2011; Thornton and Herrero 2014). Surveys of farmers in climate variable areas find that livelihood diversification is increasingly favoured as an adaptation option (Bryan et al. 2013), although it is not always successful, since it can increase exposure to climate variability (Adger et al. 2011). There are more than 570 million small farms in the world (Lowder et al. 2016), and many millions of smallholder agriculturalists already practice livelihood diversification by engaging in multiple forms of off-farm income (Rigg 2006). It is not clear, however, how many farmers have not yet practiced diversification and thus how many would be helped by supporting this response option.

Currently, millions of farmers still rely to some degree on local seeds. Use of local seeds can facilitate adaptation for many smallholders, as moving to use of commercial seeds can increase costs for farmers (Howard 2015). Seed networks and banks protect local agrobiodiversity and landraces, which are important to facilitate adaptation, as local landraces may be resilient to some forms of climate change (Coomes et al. 2015; Van Niekerk and Wynberg 2017; Vasconcelos et al. 2013).

Disaster risk management is an essential part of adaptation strategies. The Famine Early Warning Systems Network funded by the US Agency for International Development (USAID) has operated across three continents since the 1980s, and many millions of people across 34 countries have access to early information on drought. Such information can assist communities and households in adapting to onset conditions (Hillbruner and Moloney 2012). However, concerns have been raised as to how many people are actually reached by disaster risk management and early warning systems; for example, less than 50% of respondents in Bangladesh had heard a cyclone warning before it hit, even though an early warning system existed (Mahmud and Prowse 2012). Further, there are concerns that current early warning systems 'tend to focus on response and recovery rather than on addressing livelihood issues as part of the process of reducing underlying risk factors,' (Birkmann et al. 2015), leading to less adaptation potential being realised.

Local risk-sharing instruments like rotating credit or loan groups can help buffer farmers against climate impacts and help facilitate adaptation. Both index and commercial crop insurance offers some potential for adaptation, as it provides a means of buffering and transferring weather risk, saving farmers the cost of crop losses (Meze-Hausken et al. 2009; Patt et al. 2010). However, overly subsidised insurance can undermine the market's role in pricing risks and thus depress more rapid adaptation strategies (Skees and Collier 2012; Jaworski 2016) and increase the riskiness of decision-making (McLeman and Smit 2006). For example, availability of crop insurance was observed to reduce farm-level diversification in the US, a factor cited as increasing adaptive capacity (Sanderson et al. 2013) and crop insurance-holding soybean farmers in the USA have been less likely to adapt to extreme weather events than those not holding insurance (Annan and Schlenker 2015). It is unclear how many people worldwide use insurance as an adaptation strategy; Platteau et al. (2017) suggest that less than 30% of smallholders take out any form of insurance, but it is likely in the millions.

Table 6.28 summarises the impacts on adaptation of risk management options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.28 | Adaptation effects of response options based on risk management.

Integrated response option	Potential	Confidence	Citation
Management of urban sprawl	Unquantified but likely to be many millions	Low confidence	Stone et al. 2010
Livelihood diversification	>100 million likely	Low confidence	Morton 2007; Rigg 2006
Use of local seeds	Unquantified but likely to be many millions	Low confidence	Louwaars 2002; Santilli 2012
Disaster risk management	>100 million	High confidence	Hillbruner and Moloney 2012
Risk sharing instruments	Unquantified but likely to be several million	Low confidence	Platteau et al. 2017

6.3.3 Potential of the integrated response options for addressing desertification

In this section, the impacts of integrated response options on desertification are assessed.

6.3.3.1 Integrated response options based on land management

In this section, the impacts on desertification of integrated response options based on land management are assessed.

Integrated response options based on land management in agriculture

Burney et al. (2010) estimated that an additional global cropland area of 11.11–15.14 Mkm^2 would have been needed if productivity had not increased between 1961 and 2000. Given that agricultural expansion is a main driver of desertification (FAO and ITPS 2015), increased food productivity could have prevented up to 11.11–15.14 Mkm^2 from exploitation and desertification (Table 6.10).

Improved cropland, livestock and grazing land management are strategic options aimed at prevention of desertification, and may include crop and animal selection, optimised stocking rates, changed tillage and/or cover crops, to land-use shifting from cropland to rangeland, in general targeting increases in ground cover by vegetation, and protection against wind erosion (Schwilch et al. 2014; Bestelmeyer et al. 2015). Considering the widespread distribution of deserts and desertified lands globally, more than 10 Mkm^2 could benefit from improved management techniques.

Agroforestry can help stabilise soils to prevent desertification (Section 6.3.2.1), so given that there is around 10 Mkm^2 of land with more than 10% tree cover (Garrity 2012), agroforestry could benefit up to 10 Mkm^2 of land.

Agricultural diversification to prevent desertification may include the use of crops with manures, legumes, fodder legumes and cover crops combined with conservation tillage systems (Schwilch et al. 2014). These practices can be considered to be part of improved crop management options (see above) and aim at increasing ground coverage by vegetation and controlling wind erosion losses.

Since shifting from grassland to the annual cultivation of crops increases erosion and soil loss, there are significant benefits for desertification control, by stabilising soils in arid areas (Chapter 3). Cropland expansion during 1985 to 2005 was 359,000 km^2, or 17,400 $km^2\ yr^{-1}$ (Foley et al. 2011). Not all of this expansion will be from grasslands or in desertified areas, but this value sets the maximum contribution of prevention of conversion of grasslands to croplands, a small global benefit for desertification control (Table 6.10).

Integrated water management strategies such as water-use efficiency and irrigation, improve soil health through increase in soil organic matter content, thereby delivering benefits for prevention or reversal of desertification (Baumhardt et al. 2015; Datta et al. 2000; Evans and Sadler 2008; He et al. 2015) (Chapter 3). Climate change will amplify existing stress on water availability and on agricultural systems, particularly in semi-arid environments (IPCC AR5 2014) (Chapter 3). In 2011, semi-arid ecosystems in the southern hemisphere contributed 51% of the global net carbon sink (Poulter et al. 2014). These results suggest that arid ecosystems could be an important global carbon sink, depending on soil water availability.

Table 6.29 summarises the impacts on desertification of agricultural options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.29 | Effects on desertification of response options in agriculture.

Integrated response option	Potential	Confidence	Citation
Increased food productivity	11.1–15.1 Mkm^2	Low confidence	Burney et al. 2010
Improved cropland management	10 Mkm^2	Low confidence	Schwilch et al. 2014
Improved grazing land management	0.5–3 Mkm^2	Low confidence	Schwilch et al. 2014
Improved livestock management	0.5–3 Mkm^2	Low confidence	Miao et al. 2015; Squires and Karami 2005
Agroforestry	10 Mkm^2 (with >10% tree cover)	Medium confidence	Garrity 2012
Agricultural diversification	0.5–3 Mkm^2	Low confidence	Lambin and Meyfroidt 2011; Schwilch et al. 2014
Reduced grassland conversion to cropland	Up to 17,400 $km^2\ yr^{-1}$	Low confidence	Foley et al. 2011
Integrated water management	10,000 km^2	Low confidence	Pierzynski et al. 2017; UNCCD 2012

Integrated response options based on land management in forestry

Forests are important to help to stabilise land and regulate water and microclimate (Locatelli et al. 2015b). Based on the extent of dry forest at risk of desertification (Núñez et al. 2010; Bastin et al. 2017), the estimated global potential effect for avoided desertification is large for both forest management and for reduced deforestation and forest degradation when cumulated for at least 20 years (Table 6.30). The uncertainty of these global estimates is high. More robust qualitative and some quantitative estimates are available at regional level. For example, it has been simulated that human activity (i.e., land management) contributed to 26% of the total land reverted from desertification in Northern China between 1981 and 2010 (Xu et al. 2018). In Thailand, it was found that the desertification risk is reduced when the land use is changed from bare lands to agricultural lands and forests, and from non-forests to forests; conversely, the desertification risk increases when converting forests and denuded forests to bare lands (Wijitkosum 2016).

Afforestation, reforestation and forest restoration are land management response options that are used to prevent desertification. Forests tend to maintain water and soil quality by reducing runoff and trapping sediments and nutrients (Medugu et al. 2010; Salvati et al. 2014), but planting of non-native species in semi-arid regions can deplete soil water resources if they have high evapotranspiration rates (Zeng et al. 2016; Yang et al. 2014). Afforestation and reforestation programmes can be deployed over large areas of the Earth, so can create synergies in areas prone to desertification. Global estimates of land potentially available for afforestation are up to 25.8 Mkm^2 by the end of the century, depending on a variety of assumptions on socio-economic developments and climate policies (Griscom et al. 2017; Kreidenweis et al. 2016; Popp et al. 2017). The higher end of this range is achieved under the assumption of a globally uniform reward for carbon uptake in the terrestrial biosphere, and it is halved by considering tropical and subtropical areas only to minimise albedo feedbacks (Kreidenweis et al. 2016). When safeguards are introduced (e.g., excluding existing cropland for food security, boreal areas, etc.), the area available declines to about 6.8 Mkm^2 (95% confidence interval of 2.3 and 11.25 Mkm^2), of which about 4.72 Mkm^2 is in the tropics and 2.06 Mkm^2 is in temperate regions (Griscom et al. 2017) (Table 6.30).

Table 6.30 summarises the impacts on desertification of forestry options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.30 | Effects on desertification of response options in forests.

Integrated response option	Potential	Confidence	Citation
Forest management	>3 Mkm^2	Low confidence	Bastin et al. 2017; Núñez et al. 2010
Reduced deforestation and forest degradation	>3 Mkm^2 (effects cumulated for at least 20 years)	Low confidence	Bastin et al. 2017; Keenan et al. 2015; Núñez et al. 2010
Reforestation and forest restoration	See afforestation		
Afforestation	2–25.8 Mkm^2 by the end of the century	Medium confidence	Griscom et al. 2017; Kreidenweis et al. 2016; Popp et al. 2017

Integrated response options based on land management of soils

With more than 2.7 billion people affected globally by desertification (IPBES 2018), practices to increase soil organic carbon content are proposed as actions to address desertification, and could be applied to an estimated 11.37 Mkm^2 of desertified soils (Lal 2001) (Table 6.31).

Control of soil erosion could have large benefits for desertification control. Using figures from FAO et al. (2015), IPBES (2018) estimated that land losses due to erosion to 2050 are equivalent to 1.5 Mkm^2 of land from crop production, or 45,000 km^2 yr^{-1} (Foley et al. 2011) so soil erosion control could benefit up to 1.50 Mkm^2 of land in the coming decades. Lal (2001) estimated that desertification control (using soil erosion control as one intervention) could benefit 11.37 Mkm^2 of desertified land globally (Table 6.10).

Oldeman et al. (1991) estimated that the global extent soil affected by salinisation is 0.77 Mkm^2 yr^{-1}, which sets the upper limit on the area that could benefit from measures to address soil salinisation (Table 6.31).

In degraded arid grasslands, shrublands and rangelands, desertification can be reversed by alleviation of soil compaction through installation of enclosures and removal of domestic livestock (Allington et al. 2010), but there are no global estimates of potential (Table 6.31).

Biochar could potentially deliver benefits in efforts to address desertification though improving water-holding capacity (Woolf et al. 2010; Sohi 2012), but the global effect is not quantified.

Table 6.31 summarises the impacts on desertification of soil-based options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.31 | Effects on desertification of land management of soils.

Integrated response option	Potential	Confidence	Citation
Increased soil organic carbon content	Up to 11.37 Mkm^2	Medium confidence	Lal 2001
Reduced soil erosion	Up to 11.37 Mkm^2	Medium confidence	Lal 2001
Reduced soil salinisation	0.77 Mkm^2 yr^{-1}	Medium confidence	Oldeman et al. 1991
Reduced soil compaction	No global estimates	No evidence	FAO and ITPS 2015; Hamza and Anderson 2005
Biochar addition to soil	No global estimates	No evidence	

Integrated response options based on land management across all/other ecosystems

For fire management, Arora and Melton (2018) estimated, using models and GFED4.1s0 data, that burned area over the 1997–2014 period was 4.834–4.855 $Mkm^2 yr^{-1}$. Randerson et al. (2012) estimated small fires increased total burned area globally by 35% from 3.45 to 4.64 $Mkm^2 yr^{-1}$ during the period 2001–2010. Tansey et al. (2004) estimated that over 3.5 $Mkm^2 yr^{-1}$ of burned areas were detected in the year 2000 (Table 6.32).

Although slope and slope aspect are predictive factors of desertification occurrence, the factors with the greatest influence are land cover factors, such as normalised difference vegetation index (NDVI) and rangeland classes (Djeddaoui et al. 2017). Therefore, prevention of landslides and natural hazards exert indirect influence on the occurrence of desertification.

The global extent of chemical soil degradation (salinisation, pollution and acidification) is about 1.03 $Mkm^2 yr^{-1}$ (Oldeman et al. 1991), giving the maximum extent of land that could benefit from the management of pollution and acidification.

There are no global data on the impacts of management of invasive species/encroachment on desertification, though the impact is presumed to be positive. There are no studies examining the potential role of restoration and avoided conversion of coastal wetlands on desertification.

There are no impacts of peatland restoration for prevention of desertification, as peatlands occur in wet areas and deserts in arid areas, so they are not connected.

For management of pollution, including acidification, Oldeman et al. (1991) estimated the global extent of chemical soil degradation, with 0.77 $Mkm^2 yr^{-1}$ affected by salinisation, 0.21 $Mkm^2 yr^{-1}$ affected by pollution, and 0.06 $Mkm^2 yr^{-1}$ affected by acidification (total: 1.03 $Mkm^2 yr^{-1}$), so this is the area that could potentially benefit from pollution management measures.

Biodiversity conservation measures can interact with desertification, but the literature contains no global estimates of potential.

Table 6.32 summarises the impacts on desertification of options on all/other ecosystems, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.32 | Effects on desertification of response options on all/other ecosystems.

Integrated response option	Potential	Confidence	Citation
Fire management	Up to 3.5–4.9 $Mkm^2 yr^{-1}$	Medium confidence	Arora and Melton 2018; Randerson et al. 2012; Tansey et al. 2004
Reduced landslides and natural hazards	>0	Low confidence	Djeddaoui et al. 2017; Noble et al. 2014
Reduced pollution including acidification	1.03 $Mkm^2 yr^{-1}$	Low confidence	Oldeman et al. 1991
Management of invasive species/encroachment	No global estimates	No evidence	
Restoration and reduced conversion of coastal wetlands	No global estimates	No evidence	
Restoration and reduced conversion of peatlands	No impact		
Biodiversity conservation	No global estimates	No evidence	

Integrated response options based on land management specifically for carbon dioxide removal (CDR)

While spreading of crushed minerals onto land as part of enhanced weathering may provide soil/plant nutrients in nutrient-depleted soils (Beerling et al. 2018), there is no literature reporting on the potential global impacts of this in addressing desertification.

Large-scale production of bioenergy can require significant amounts of land (Smith et al. 2016a; Clarke et al. 2014; Popp et al. 2017), with as much as 15 Mkm^2 in 2100 in 2°C scenarios (Popp et al. 2017), increasing pressures for desertification (Table 6.33).

Table 6.33 summarises the impacts on desertification of options specifically for CDR, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.33 | Effects on desertification of response options specifically for CDR.

Integrated response option	Potential	Confidence	Citation
Enhanced weathering of minerals	No global estimates	No evidence	
Bioenergy and BECCS	Negative impact on up to 15 Mkm^2	Low confidence	Clarke et al. 2014; Popp et al. 2017; Smith et al. 2016a

6.3.3.2 Integrated response options based on value chain management

In this section, the impacts on desertification of integrated response options based on value chain management are assessed.

Integrated response options based on value chain management through demand management

Dietary change and waste reduction both result in decreased cropland and pasture extent (Bajželj et al. 2014a; Stehfest et al. 2009; Tilman and Clark 2014), reducing the pressure for desertification (Table 6.34).

Reduced post-harvest losses could spare 1.98 Mkm^2 of cropland globally (Kummu et al. 2012). Not all of this land could be subject to desertification pressure, so this represents the maximum area that could be relieved from desertification pressure by reduction of post-harvest losses. No studies were found linking material substitution to desertification.

Table 6.34 summarises the impacts on desertification of demand management options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.34 | Effects on desertification of response options based on demand management.

Integrated response option	Potential	Confidence	Citation
Dietary change	0.80–5 Mkm^2	Low confidence	Alexander et al. 2016; Bajželj et al. 2014b; Stehfest et al. 2009; Tilman and Clark 2014
Reduced post-harvest losses	<1.98 Mkm^2	Low confidence	Kummu et al. 2012
Reduced food waste (consumer or retailer)	1.4 Mkm^2	Low confidence	Bajželj et al. 2014b
Material substitution	No global estimates	No evidence	

Integrated response options based on value chain management through supply management

There are no global estimates of the impact on desertification of sustainable sourcing, management of supply chains, enhanced urban food systems, improved food processing, or improved energy use in agriculture.

Table 6.35 summarises the impacts on desertification of supply management options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.35 | Effects on desertification of response options based on supply management.

Integrated response option	Potential	Confidence	Citation
Sustainable sourcing	No global estimates	No evidence	
Management of supply chains	No global estimates	No evidence	
Enhanced urban food systems	No global estimates	No evidence	
Improved food processing and retailing	No global estimates	No evidence	
Improved energy use in food systems	No global estimates	No evidence	

6.3.3.3 Integrated response options based on risk management

In this section, the impacts on desertification of integrated response options based on risk management are assessed.

There are regional case studies of urban sprawl contributing to desertification in Mediterranean climates in particular (Barbero-Sierra et al. 2013; Stellmes et al. 2013), but no global figures.

Diversification may deliver some benefits for addressing desertification when it involves greater use of tree crops that may reduce the need for tillage (Antwi-Agyei et al. 2014). Many anti-desertification programmes call for diversification (Stringer et al. 2009), but there is little evidence on how many households had done so (Herrmann and Hutchinson 2005). There are no numbers for global impacts.

The literature is unclear on whether the use of local seeds has any relationship to desertification, although some local seeds are more likely to adapt to arid climates and less likely to degrade land than commercially introduced varieties (Mousseau 2015). Some anti-desertification programmes have also shown more success using local seed varieties (Bassoum and Ghiggi 2010; Nunes et al. 2016).

Some disaster risk management approaches can have impacts on reducing desertification, like the Global Drought Early Warning System (GDEWS) (currently in development), which will monitor precipitation, soil moisture, evapotranspiration, river flows, groundwater, agricultural productivity and natural ecosystem health. It may have some potential co-benefits to reduce desertification (Pozzi et al. 2013). However, there are no figures yet for how much land area will be covered by such early warning systems.

Risk-sharing instruments, such as pooling labour or credit, could help communities invest in anti-desertification actions, but evidence is missing. Commercial crop insurance is likely to deliver no co-benefits for prevention and reversal of desertification, as evidence suggests that subsidised insurance, in particular, can increase crop production in marginal lands. Crop insurance could have been responsible for shifting up to 0.9% of rangelands to cropland in the Upper Midwest of the USA (Claassen et al. 2011a).

Table 6.36 summarises the impact on desertification for options based on risk management, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.36 | Effects on desertification of response options based on risk management.

Integrated response option	Potential	Confidence	Citation
Management of urban sprawl	>5000 km^2	Low confidence	Barbero-Sierra et al. 2013
Livelihood diversification	No global estimates	Low confidence	Herrmann and Hutchinson 2005
Use of local seeds	No global estimates	No evidence	
Disaster risk management	No global estimates	No evidence	Pozzi et al. 2013
Risk-sharing instruments	Likely negative impacts but not quantified	Low confidence	Claassen et al. 2011a

6.3.4 Potential of the integrated response options for addressing land degradation

In this section, the impacts of integrated response options on land degradation are assessed.

6.3.4.1 Integrated response options based on land management

In this section, the impacts on land degradation of integrated response options based on land management are assessed.

Integrated response options based on land management in agriculture

Burney et al. (2010) estimated that an additional global cropland area of 11.11–15.14 Mkm^2 would have been needed if productivity had not increased between 1961 and 2000. As for desertification, given that agricultural expansion is a main driver of land degradation (FAO and ITPS 2015), increased food productivity has prevented up to 11.11–15.14 Mkm^2 from exploitation and land degradation (Table 6.37).

Land degradation can be addressed by the implementation of improved cropland, livestock and grazing land management practices, such as those outlined in the recently published Voluntary Guidelines for Sustainable Soil Management (FAO 2017b). Each one could potentially affect extensive surfaces, not less than 10 Mkm^2. The guidelines include a list of practices aimed at minimising soil erosion, enhancing soil organic matter content, fostering soil nutrient balance and cycles, preventing, minimising and mitigating soil salinisation and alkalinisation, soil contamination, soil acidification, soil sealing, soil compaction, and improving soil water management. Land cover and land cover change are key factors and indicators of land degradation. In many drylands, land cover is threatened by overgrazing, so management of stocking rate and grazing can help to prevent the advance of land degradation (Smith et al. 2016a).

Agroforestry can help stabilise soils to prevent land degradation; so, given that there is around 10 Mkm^2 of land with more than 10% tree cover (Garrity 2012), agroforestry could benefit up to 10 Mkm^2 of land.

Agricultural diversification usually aims at increasing climate and food security resilience, such as under 'climate smart agriculture' approaches (Lipper et al. 2014). Both objectives are closely related to land degradation prevention, potentially affecting 1–5 Mkm^2.

Shifting from grassland to tilled crops increases erosion and soil loss, so there are significant benefits for addressing land degradation, by stabilising degraded soils (Chapter 3). Since cropland expansion during 1985 to 2005 was 17,400 km^2 yr^{-1} (Foley et al. 2011) – and not all of this expansion will be from grasslands or degraded land – the maximum contribution of prevention of conversion of grasslands to croplands is 17,400 km^2 yr^{-1}, a small global benefit for control of land degradation (Table 6.37).

Most land degradation processes that are sensitive to climate change pressures (e.g., erosion, decline in soil organic matter, salinisation, waterlogging, drying of wet ecosystems) can benefit from integrated water management. Integrated water management options include management to reduce aquifer and surface water depletion, and to prevent over-extraction, and provide direct co-benefits for prevention of land degradation. Land management practices implemented for climate change mitigation may also affect water resources. Globally, water erosion is estimated to result in the loss of 23–42 MtN and 14.6–26.4 MtP annually (Pierzynski et al. 2017). Forests influence the storage and flow of water in watersheds (Eisenbies et al. 2007) and are therefore important for regulating how climate change will impact on landscapes.

Table 6.37 summarises the impact on land degradation of options in agriculture, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.37 | Effects on land degradation of response options in agriculture.

Integrated response option	Potential	Confidence	Citation
Increased food productivity	11.11–15.14 Mkm^2	Medium confidence	Burney et al. 2010
Improved cropland management	10 Mkm^2	Low confidence	Lal 2015; Smith et al. 2016a
Improved grazing land management	10 Mkm^2	Low confidence	Smith et al. 2016a
Improved livestock management	10 Mkm^2	Low confidence	Lal 2015; Smith et al. 2016a
Agroforestry	10 Mkm^2 (with >10% tree cover)	Medium confidence	Garrity 2012
Agricultural diversification	1–5 Mkm^2	Medium confidence	Lambin and Meyfroidt 2011
Reduced grassland conversion to cropland	Up to 17,400 km^2 yr^{-1}	Low confidence	Foley et al. 2011
Integrated water management	0.01 Mkm^2	Medium confidence	Pierzynski et al. 2017; UNCCD 2012

Integrated response options based on land management in forestry

Based on the extent of forest exposed to degradation (Gibbs and Salmon 2015), the estimated global potential effect for reducing land degradation, for example, through reduced soil erosion (Borrelli et al. 2017), is large for both forest management and for reduced deforestation and forest degradation when cumulated for at least 20 years (Table 6.38). The uncertainty of these global estimates is high. More robust qualitative, and some quantitative, estimates are available at regional level. For example, in Indonesia, Santika et al. (2017) demonstrated that reduced deforestation (Sumatra and Kalimantan islands) contributed to significantly reduced land degradation.

Forest restoration is a key option to achieve the overarching frameworks to reduce land degradation at global scale, such as, for example, Zero Net Land Degradation (ZNLD; UNCCD 2012) and Land Degradation Neutrality (LDN), not only in drylands (Safriel 2017). Indeed, it has been estimated that more than 20 Mkm^2 are suitable for forest and landscape restoration, of which 15 Mkm^2 may be devoted to mixed plant mosaic restoration (UNCCD 2012). Moreover, the Bonn Challenge[6] aims to restore 1.5 Mkm^2 of deforested and degraded land by 2020, and 3.5 Mkm^2 by 2030. Under a restoration and protection scenario (implementing restoration targets), Wolff et al. (2018) simulated that there will be a global increase in net tree cover of about 4 Mkm^2 by 2050 (Table 6.38). At local level, Brazil's Atlantic Restoration Pact aims to restore 0.15 Mkm^2 of forest areas in 40 years (Melo et al. 2013). The Y Ikatu Xingu campaign (launched in 2004) aims to contain deforestation and forest degradation processes by reversing the liability of 3000 km^2 in the Xingu Basin, Brazil (Durigan et al. 2013).

Afforestation and reforestation are land management options frequently used to address land degradation (see Section 6.3.3.1 for details, and Table 6.38).

Table 6.38 summarises the impact on land degradation of options in forestry, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.38 | Effects on land degradation of response options in forestry.

Integrated response option	Potential	Confidence	Citation
Forest management	>3 Mkm^2	Low confidence	Gibbs and Salmon 2015
Reduced deforestation and forest degradation	>3 Mkm^2 (effects cumulated for at least 20 years)	Low confidence	Gibbs and Salmon 2015; Keenan et al. 2015
Reforestation and forest restoration	20 Mkm^2 suitable for restoration >3 Mkm^2 by 2050 (net increase in tree cover for forest restoration)	Medium confidence	UNCCD 2012; Wolff et al. 2018
Afforestation	2–25.8 Mkm^2 by the end of the century	Low confidence	Griscom et al. 2017; Kreidenweis et al. 2016; Popp et al. 2017

Integrated response options based on land management of soils

Increasing soil organic matter content is a measure to address land degradation. With around 120,000 km^2 lost to degradation every year, and over 3.2 billion people negatively impacted on by land degradation globally (IPBES 2018), practices designed to increase soil organic carbon have a large potential to address land degradation, estimated to affect more than 11 Mkm^2 globally (Lal 2004) (Table 6.39).

Control of soil erosion could have large benefits for addressing land degradation. Soil erosion control could benefit up to 1.50 Mkm^2 of land to 2050 (IPBES 2018). Lal (2004) suggested that interventions to prevent wind and water erosion (two of the four main interventions proposed to address land degradation), could restore 11 Mkm^2 of degraded and desertified soils globally (Table 6.39).

Oldeman et al. (1991) estimated that the global extent soil affected by salinisation is 0.77 Mkm^2 yr^{-1}, which sets the upper limit on the area that could benefit from measures to address soil salinisation (Table 6.39). The global extent of chemical soil degradation (salinisation, pollution and acidification) is about 1.03 Mkm^2 (Oldeman et al. 1991) giving the maximum extent of land that could benefit from the management of pollution and acidification.

[6] www.bonnchallenge.org/content/challenge.

Biochar could provide moderate benefits for the prevention or reversal of land degradation, by improving water-holding capacity and nutrient-use efficiency, managing heavy metal pollution, and other co-benefits (Sohi 2012), though the global effects are not quantified.

Table 6.39 summarises the impact on land degradation of soil-based options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.39 | Effects on land degradation of soil-based response options.

Integrated response option	Potential	Confidence	Citation
Increased soil organic carbon content	11 Mkm^2	Medium confidence	Lal 2004
Reduced soil erosion	11 Mkm^2	Medium confidence	Lal 2004
Reduced soil salinisation	0.77 Mkm^2 yr^{-1}	Medium confidence	FAO 2018a; Qadir et al. 2013
Reduced soil compaction	10 Mkm^2	Low confidence	FAO and ITPS 2015; Hamza and Anderson 2005
Biochar addition to soil	Positive but not quantified globally	Low confidence	Chapter 4

Integrated response options based on land management across all/other ecosystems

For fire management, details of estimates of the impact of wildfires (and thereby the potential impact of their suppression) are given in Section 6.3.3.1 (Table 6.40).

Management of landslides and natural hazards aims at controlling a severe land degradation process affecting sloped and hilly areas, many of them with poor rural inhabitants (FAO and ITPS 2015; Gariano and Guzzetti 2016), but the global potential has not been quantified.

There are no global data on the impacts of management of invasive species/encroachment on land degradation, though the impact is presumed to be positive.

Since large areas of coastal wetlands are degraded, restoration could potentially deliver moderate benefits for addressing land degradation, with 0.29 Mkm^2 globally considered feasible for restoration (Griscom et al. 2017) (Table 6.40).

Considering that large areas (0.46 Mkm^2) of global peatlands are degraded and considered suitable for restoration (Griscom et al. 2017), peatland restoration could deliver moderate benefits for addressing land degradation (Table 6.40).

There are no global estimates of the effects of biodiversity conservation on reducing degraded lands. However, at local scale, biodiversity conservation programmes have been demonstrated to stimulate gain of forest cover across large areas over the last three decades (e.g., in China; Zhang et al. 2013). Management of wild animals can influence land degradation processes by grazing, trampling and compacting soil surfaces, thereby altering surface temperatures and chemical reactions affecting sediment and carbon retention (Cromsigt et al. 2018).

Table 6.40 summarises the impact on land degradation of options in all/other ecosystems, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.40 | Effects on land degradation of response options in all/other ecosystems.

Integrated response option	Potential	Confidence	Citation
Fire management	Up to 3.5–4.9 Mkm^2 yr^{-1}	Medium confidence	Arora and Melton 2018; Randerson et al. 2012; Tansey et al. 2004
Reduced landslides and natural hazards	1–5 Mkm^2	Low confidence	FAO and ITPS 2015; Gariano and Guzzetti 2016
Reduced pollution including acidification	~1.03 Mkm^2	Low confidence	Oldeman et al. 1991
Management of invasive species/encroachment	No global estimates	No evidence	
Restoration and reduced conversion of coastal wetlands	0.29 Mkm^2	Medium confidence	Griscom et al. 2017
Restoration and reduced conversion of peatlands	0.46 Mkm^2	Medium confidence	Griscom et al. 2017
Biodiversity conservation	No global estimates	No evidence	

Integrated response options based on land management specifically for carbon dioxide removal (CDR)

While spreading of crushed minerals onto land as part of enhanced weathering can provide soil/plant nutrients in nutrient-depleted soils, increase soil organic carbon stocks and help to replenish eroded soil (Beerling et al. 2018), there is no literature on the global potential for addressing land degradation.

Large-scale production of bioenergy can require significant amounts of land (Smith et al. 2016a; Clarke et al. 2014; Popp et al. 2017) – as much as 15 Mkm^2 in 2°C scenarios (Popp et al. 2017) – therefore increasing pressures for land conversion and land degradation (Table 6.13). However, bioenergy production can either increase (Robertson et al. 2017b; Mello et al. 2014) or decrease (FAO 2011b; Lal 2014) soil organic matter, depending on where it is produced and how it is managed. These effects are not included in the quantification in Table 6.41.

Table 6.41 summarises the impact on land degradation of options specifically for CDR, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.41 | Effects on land degradation of response options specifically for CDR.

Integrated response option	Potential	Confidence	Citation
Enhanced weathering of minerals	Positive but not quantified	Low confidence	Beerling et al. 2018
Bioenergy and BECCS	Negative impact on up to 15 Mkm^2	Low confidence	Clarke et al. 2014; Popp et al. 2017; Smith et al. 2016a

6.3.4.2 Integrated response options based on value chain management

In this section, the impacts on land degradation of integrated response options based on value chain management are assessed.

Integrated response options based on value chain management through demand management

Dietary change and waste reduction both result in decreased cropland and pasture extent (Bajželj et al. 2014a; Stehfest et al. 2009; Tilman and Clark 2014), reducing the pressure for land degradation (Table 6.15). Reduced post-harvest losses could spare 1.98 Mkm^2 of cropland globally (Kummu et al. 2012) meaning that land degradation pressure could be relieved from this land area through reduction of post-harvest losses. The effects of material substitution on land degradation depend on management practice; some forms of logging can lead to increased land degradation (Chapter 4).

Table 6.42 summarises the impact on land degradation of demand management options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.42 | Effects on land degradation of response options based on demand management.

Integrated response option	Potential	Confidence	Citation
Dietary change	4–28 Mkm^2	High confidence	Alexander et al. 2016; Bajželj et al. 2014b; Stehfest et al. 2009; Tilman and Clark 2014
Reduced post-harvest losses	1.98 Mkm^2	Medium confidence	Kummu et al. 2012
Reduced food waste (consumer or retailer)	7 Mkm^2	Medium confidence	Bajželj et al. 2014b
Material substitution	No global estimates	No evidence	

Integrated response options based on value chain management through supply management

There are no global estimates of the impact on land degradation of enhanced urban food systems, improved food processing, retailing, or improved energy use in food systems.

There is evidence that sustainable sourcing could reduce land degradation, as the explicit goal of sustainable certification programmes is often to reduce deforestation or other unsustainable land uses. Over 4 Mkm^2 of forests are certified for sustainable harvesting (PEFC and FSC 2018), although it is not clear if all these lands would be at risk of degradation without certification. While the food price instability of 2007/2008 increased financial investment in crop expansion (especially through so-called land grabbing), and thus better management of supply chains might have reduced this amount, no quantification of the total amount of land acquired, nor the possible impact of this crop expansion on degradation, has been recorded (McMichael and Schneider 2011; McMichael 2012).

Table 6.43 summarises the impact on land degradation of supply management options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.43 | Effects on land degradation of response options based on supply management.

Integrated response option	Potential	Confidence	Citation
Sustainable sourcing	>4 Mkm^2	Low confidence	Auld et al. 2008
Management of supply chains	No global estimates	No evidence	
Enhanced urban food systems	No global estimates	No evidence	
Improved food processing and retailing	No global estimates	No evidence	
Improved energy use in food systems	No global estimates	No evidence	

6.3.4.3 Integrated response options based on risk management

In this section, the impacts on land degradation of integrated response options based on risk management are assessed.

Urban expansion has been identified as a major culprit in soil degradation in some countries; for example, urban expansion in China has now affected 0.2 Mkm^2, or almost one-sixth of the cultivated land total, causing an annual grain yield loss of up to 10 Mt, or around 5–6% of cropland production. Cropland production losses of 8–10% by 2030 are expected under model scenarios of urban expansion (Bren d'Amour et al. 2016). Pollution from urban development has included water and soil pollution from industry, and wastes and sewage, as well as acid deposition from increasing energy use in cities (Chen 2007), all resulting in major losses to Nature's Contributions to People from urban conversion (Song and Deng 2015). Soil sealing from urban expansion is a major loss of soil productivity across many areas. The World Bank has estimated that new city dwellers in developing countries will require 160–500 m^2 per capita, converted from non-urban to urban land (Barbero-Sierra et al. 2013; Angel et al. 2005).

Degradation can be a driver leading to livelihood diversification (Batterbury 2001; Lestrelin and Giordano 2007). Diversification has the potential to deliver some reversal of land degradation, if diversification involves adding non-traditional crops or trees that may reduce the need for tillage (Antwi-Agyei et al. 2014). China's Sloping Land Conversion Program has had livelihood diversification benefits and is said to have prevented degradation of 93,000 km^2 of land (Liu et al. 2015). However, Warren (2002) provides conflicting evidence that more diverse-income households had increased degradation on their lands in Niger. Palacios et al. (2013) associate landscape fragmentation with increased livelihood diversification in Mexico.

Use of local seeds may play a role in addressing land degradation due to the likelihood of local seeds being less dependent on inputs such as chemical fertilisers or mechanical tillage; for example, in India, local legumes are retained in seed networks while commercial crops like sorghum and rice dominate food markets (Reisman 2017). However, there are no global figures.

Disaster Risk Management systems can have some positive impacts on prevention and reversal of land degradation, such as the Global Drought Early Warning System (Pozzi et al. 2013) (Section 6.3.3.3).

Risk-sharing instruments could have benefits for reduced degradation, but there are no global estimates. Commercial crop insurance is likely to deliver no co-benefits for prevention and reversal of degradation. One study found a 1% increase in farm receipts generated from subsidised farm programmes (including crop insurance and others) increased soil erosion by 0.3 t ha^{-1} (Goodwin and Smith 2003). Wright and Wimberly (2013) found a 5310 km^2 decline in grasslands in the Upper Midwest of the USA during 2006–2010, due to crop conversion driven by higher prices and access to insurance.

Table 6.44 summarises the impact on land degradation of risk management options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.44 | Effects on land degradation of response options based on risk management.

Integrated response option	Potential	Confidence	Citation
Management of urban sprawl	>0.2 Mkm^2	Medium confidence	Chen 2007; Zhang et al. 2000
Livelihood diversification	>0.1 Mkm^2	Low confidence	Liu and Lan 2015
Use of local seeds	No global estimates	No evidence	
Disaster risk management	No global estimates	No evidence	Pozzi et al. 2013
Risk-sharing instruments	Variable, but negative impact on >5000 km^2 in Upper Midwest USA	Low confidence	Goodwin and Smith 2003; Wright and Wimberly 2013

6.3.5 Potential of the integrated response options for addressing food security

In this section, the impacts of integrated response options on food security are assessed.

6.3.5.1 Integrated response options based on land management

In this section, the impacts on food security of integrated response options based on land management are assessed.

Integrated response options based on land management in agriculture

Increased food productivity has fed many millions of people who would otherwise not have been fed. Erisman et al. (2008) estimated that more than 3 billion people worldwide could not have been fed without increased food productivity arising from nitrogen fertilisation (Table 6.45).

Improved cropland management to achieve food security aims at closing yield gaps by increasing use efficiency of essential inputs such as water and nutrients. Large production increases (45–70% for most crops) are possible from closing yield gaps to 100% of attainable yield, by increasing fertiliser use and irrigation, but overuse of nutrients could cause adverse environmental impacts (Mueller et al. 2012). This improvement can impact on 1000 million people.

Improved grazing land management includes grasslands, rangelands and shrublands, and all sites on which pastoralism is practiced. In general terms, continuous grazing may cause severe damage to topsoil quality, for example, through compaction. This damage may be reversed by short grazing-exclusion periods under rotational grazing systems (Greenwood and McKenzie 2001; Drewry 2006; Taboada et al. 2011). Due to the widespread diffusion of pastoralism, improved grassland management may potentially affect more than 1000 million people, many of them under subsistence agricultural systems.

Meat, milk, eggs and other animal products, including fish and other seafoods, will play an important role in achieving food security (Reynolds et al. 2015). Improved livestock management with different animal types and feeds may also impact on one million people (Herrero et al. 2016). Ruminants are efficient converters of grass into human-edible energy, and protein and grassland-based food production can produce food with a comparable carbon footprint to mixed systems (O'Mara 2012). However, in the future, livestock production will increasingly be affected by competition for natural resources, particularly land and water, competition between food and feed, and by the need to operate in a carbon-constrained economy (Thornton et al. 2009).

Currently, more than 1.3 billion people are on degrading agricultural land, and the combined impacts of climate change and land degradation could reduce global food production by 10% by 2050. Since agroforestry could help to address land degradation, up to 1.3 billion people could benefit in terms of food security through agroforestry.

Agricultural diversification is not always economically viable; technological, biophysical, educational and cultural barriers may emerge that limit the adoption of more diverse farming systems by farmers (Section 6.4.1). Nevertheless, diversification could benefit 1000 million people, many of them under subsistence agricultural systems (Birthal et al. 2015; Massawe et al. 2016; Waha et al. 2018).

Cropland expansion during 1985 to 2005 was 17,000 km^2 yr^{-1} (Foley et al. 2005). Given that cropland productivity (global average of 250 kg protein ha^{-1} yr^{-1} for wheat; Clark and Tilman 2017) is greater than that of grassland (global average of about 10 kg protein ha^{-1} yr^{-1} for beef/mutton; Clark and Tilman 2017), prevention of this conversion to cropland would have led to a loss of about 0.4 Mt protein yr^{-1} globally. Given an average protein consumption in developing countries of 25.5 kg protein yr^{-1} (equivalent to 70 g person^{-1} day^{-1}; FAO 2018b; OECD and FAO 2018), this is equivalent to the protein consumption of 16.4 million people each year (Table 6.45).

Integrated water management provides direct benefits to food security by improving agricultural productivity (Chapter 5; Godfray and Garnett 2014; Tilman et al. 2011), thereby potentially impacting on the livelihood and well-being of more than 1000 million people (Campbell et al. 2016) affected by hunger and highly impacted on by climate change. Increasing water availability and reliable supply of water for agricultural production using different techniques of water harvesting, storage, and its judicious utilisation through farm ponds, dams and community tanks in rainfed agriculture areas have been presented by Rao et al. (2017a) and Rivera-Ferre et al. (2016).

Table 6.45 summarises the impact on food security of options in agriculture, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.45 | Effects on food security of response options in agriculture.

Integrated response option	Potential	Confidence	Citation
Increased food productivity	3000 million people	High confidence	Erisman et al. 2008
Improved cropland management	>1000 million people	Low confidence	Campbell et al. 2014; Lipper et al. 2014
Improved grazing land management	>1000 million people	Low confidence	Herrero et al. 2016
Improved livestock management	>1000 million people	Low confidence	Herrero et al. 2016
Agroforestry	Up to 1300 million people	Low confidence	Sascha et al. 2017
Agricultural diversification	>1000 million people	Low confidence	Birthal et al. 2015; Massawe et al. 2016; Waha et al. 2018
Reduced grassland conversion to cropland	Negative impact on 16.4 million people	Low confidence	Clark and Tilman 2017; FAO 2018b
Integrated water management	>1000 million people	High confidence	Campbell et al. 2016

Integrated response options based on land management in forestry

Forests play a major role in providing food to local communities (non-timber forest products, mushrooms, fodder, fruits, berries, etc.), and diversify daily diets directly or indirectly through improving productivity, hunting, diversifying tree-cropland-livestock systems, and grazing in forests. Based on the extent of forest contributing to food supply, considering the people undernourished (FAO et al. 2013; Rowland et al. 2017), and the annual deforestation rate (Keenan et al. 2015), the global potential to enhance food security is moderate for forest management and small for reduced deforestation (Table 6.46). The uncertainty of these global estimates is high. More robust qualitative, and some quantitative, estimates are available at regional level. For example, managed natural forests, shifting cultivation and agroforestry systems are demonstrated to be crucial to food security and nutrition for hundreds of millions of people in rural landscapes worldwide (Sunderland et al. 2013; Vira et al. 2015). According to Erb et al. (2016), deforestation would not be needed to feed the global population by 2050, in terms of quantity and quality of food. At local level, Cerri et al. (2018) suggested that reduced deforestation, along with integrated cropland-livestock management, would positively impact on more than 120 million people in the Cerrado, Brazil. In Sub-Saharan Africa, where population and food demand are projected to continue to rise substantially, reduced deforestation may have strong positive effects on food security (Doelman et al. 2018).

Afforestation and reforestation negatively impact on food security (Boysen et al. 2017a; Frank et al. 2017; Kreidenweis et al. 2016). It is estimated that large-scale afforestation plans could cause increases in food prices of 80% by 2050 (Kreidenweis et al. 2016), and more general mitigation measures in the agriculture, forestry and other land-use (AFOLU) sector can translate into a rise in undernourishment of 80–300 million people (Frank et al. 2017) (Table 6.16). For reforestation, the potential adverse side effects with food security are smaller than afforestation, because forest regrows on recently deforested areas, and its impact would be felt mainly through impeding possible expansion of agricultural areas. On a smaller scale, forested land also offers benefits in terms of food supply, especially when forest is established on degraded land, mangroves and other land that cannot be used for agriculture. For example, food from forests represents a safety net during times of food and income insecurity (Wunder et al. 2014) and wild harvested meat and freshwater fish provides 30–80% of protein intake for many rural communities (McIntyre et al. 2016; Nasi et al. 2011).

Table 6.46 summarises the impact on food security of options in forestry, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.46 | Effects on food security of response options in forestry.

Integrated response option	Potential	Confidence	Citation
Forest management	Positive impact on <100 million people	Low confidence	FAO et al. 2013; Rowland et al. 2017
Reduced deforestation and forest degradation	Positive impact on <1 million people	Low confidence	FAO et al. 2013; Keenan et al. 2015; Rowland et al. 2017
Reforestation and forest restoration	See Afforestation		
Afforestation	Negative impact on >100 million people	Medium confidence	Boysen et al. 2017a; Frank et al. 2017; Kreidenweis et al. 2016

Integrated response options based on land management of soils

Increasing soil organic matter stocks can increase yield and improve yield stability (Lal 2006; Pan et al. 2009; Soussana et al. 2019), though this is not universally seen (Hijbeek et al. 2017), Lal (2006) concludes that crop yields can be increased by 20–70 kg ha^{-1}, 10–50 kg ha^{-1} and 30–300 kg ha^{-1} for wheat, rice and maize, respectively, for every 1 tC ha^{-1} increase in soil organic carbon in the root zone. Increasing soil organic carbon by 1 tC ha^{-1} could increase food grain production in developing countries by 32 Mt yr^{-1} (Lal 2006). Frank et al. (2017) estimate that soil carbon sequestration could reduce calorie loss associated with agricultural mitigation measures by 65%, saving 60–225 million people from undernourishment compared to a baseline without soil carbon sequestration (Table 6.47).

Lal (1998) estimated the risks of global annual loss of food production due to accelerated erosion to be as high as 190 Mt yr^{-1} of cereals, 6 Mt yr^{-1} of soybean, 3 Mt yr^{-1} of pulses and 73 Mt yr^{-1} of roots and tubers. Considering only cereals, if we estimate per-capita annual grain consumption in developing countries to be 300 kg yr^{-1} (based on data included in FAO 2018b; FAO et al. 2018; Pradhan et al. 2013; World Bank 2018a), the loss of 190 Mt yr^{-1} of cereals is equivalent to that consumed by 633 million people, annually (Table 6.47).

Though there are biophysical barriers, such as access to appropriate water sources and limited productivity of salt-tolerant crops, prevention/reversal of soil salinisation could benefit 1–100 million people (Qadir et al. 2013). Soil compaction affects crop yields, so prevention of compaction could also benefit an estimated 1–100 million people globally (Anderson and Peters 2016).

Biochar on balance, could provide moderate benefits for food security by improving yields by 25% in the tropics, but with more limited impacts in temperate regions (Jeffery et al. 2017), or through improved water-holding capacity and nutrient-use efficiency (Sohi 2012) (Chapter 5). These benefits could, however, be tempered by additional pressure on land if large quantities of biomass are required as feedstock for biochar production, thereby causing potential conflicts with food security (Smith 2016). Smith (2016) estimated that 0.4–2.6 Mkm^2 of land would be required for biomass feedstock to deliver 2.57 $GtCO_2e$ yr^{-1} of CO_2 removal. If biomass production occupied 2.6 Mkm^2 of cropland, equivalent to around 20% of the global cropland area, this could potentially have a large effect on food security, although Woolf et al. (2010) argue that abandoned cropland could be used to supply biomass for biochar, thus avoiding competition with food production. Similarly, Woods et al. (2015) estimate that 5–9 Mkm^2 of land is available for biomass production without compromising food security and biodiversity, considering marginal and degraded land and land released by pasture intensification (Table 6.47).

Table 6.47 summarises the impact on food security of soil-based options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.47 | Effects on food security of soil-based response options.

Integrated response option	Potential	Confidence	Citation
Increased soil organic carbon content	60–225 million people	Low confidence	Frank et al. 2017
Reduced soil erosion	633 million people yr^{-1}	Low confidence	FAO 2018b; FAO et al. 2018; Lal 1998; Pradhan et al. 2013; World Bank 2018a
Reduced soil salinisation	1–100 million people	Low confidence	Qadir et al. 2013
Reduced soil compaction	1–100 million people	Low confidence	Anderson and Peters 2016
Biochar addition to soil	Range from positive impact in the tropics from biochar addition to soil to a maximum potential negative impact on >100 million people by worst-case conversion of 20% of global cropland	Low confidence	Jeffery et al. 2017; worse-case negative impacts calculated from area values in Smith 2016

Integrated response options based on land management across all/other ecosystems

FAO (2015) calculated that damage from forest fires between 2003 and 2013 impacted on a total of 49,000 km^2 of crops, with the vast majority in Latin America. Based on the world cereal yield in 2013 reported by Word Bank (2018b) (3.8 t ha^{-1}), the loss of 49,000 km^2 of crops is equivalent to 18.6 Mt yr^{-1} of cereals lost. Assuming annual grain consumption per capita to be 300 kg yr^{-1} (estimated, based on data included in FAO 2018b; FAO et al. 2018; Pradhan et al. 2013; World Bank 2018a), the loss of 18.6 Mt yr^{-1} would remove cereal crops equivalent to that consumed by 62 million people (Table 6.48).

Landslides and other natural hazards affect 1–100 million people globally, so preventing them could provide food security benefits to these people.

In terms of measures to tackle pollution, including acidification, Shindell et al. (2012) considered about 400 emission control measures to reduce ozone and black carbon (BC). This strategy increases annual crop yields by 30–135 Mt due to ozone reductions in 2030 and beyond. If annual grain consumption per capita is assumed as 300 kg yr^{-1} (estimated based on data included in FAO 2018b; FAO et al. 2018; Pradhan et al. 2013; World Bank 2018a), increase in annual crop yields by 30–135 Mt would feed 100–450 million people.

There are no global data on the impacts of management of invasive species/encroachment on food security.

Since large areas of converted coastal wetlands are used for food production (e.g., mangroves converted for aquaculture; Naylor et al. 2000), restoration of coastal wetlands could displace food production and damage local food supply, potentially leading to adverse impacts on food security. However, these effects are likely to be very small, given that only 0.3% of human food comes from the oceans and other aquatic ecosystems (Pimentel 2006), and that the impacts could be offset by careful management, such as the careful siting of ponds within mangroves (Naylor et al. 2000) (Table 6.46).

Around 14–20% (0.56–0.80 Mkm^2) of the global 4 Mkm^2 of peatlands are used for agriculture, mostly for meadows and pasture, meaning that, if all of these peatlands were removed from production, 0.56–0.80 Mkm^2 of agricultural land would be lost. Assuming livestock production on this land (since it is mostly meadow and pasture) with a mean productivity of 9.8 kg protein ha^{-1} yr^{-1} (calculated from land footprint of beef/mutton (Clark and Tilman 2017), and average protein consumption in developing countries of 25.5 kg protein yr^{-1} (equivalent to 70 g per person per day; (FAO 2018b; OECD and FAO 2018)), this would be equivalent to 21–31 million people no longer fed from this land (Table 6.46)).

There are no global estimates on how biodiversity conservation improves nutrition (i.e., the number of nourished people). Biodiversity, and its management, is crucial for improving sustainable and diversified diets (Global Panel on Agriculture and Food Systems for Nutrition 2016). Indirectly, the loss of pollinators (due to combined causes, including the loss of habitats and flowering species) would contribute to 1.42 million additional deaths per year from non-communicable and malnutrition-related diseases, and 27.0 million lost disability-adjusted life years (DALYs) per year (Smith et al. 2015). However, at the same time, some options to preserve biodiversity, like protected areas, may potentially conflict with food production by local communities (Molotoks et al. 2017).

Table 6.48 summarises the impact on food security of response options in all/other ecosystems, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence is based.

Table 6.48 | Effects on food security of response options in all/other ecosystems.

Integrated response option	Potential	Confidence	Citation
Fire management	~62 million people	Low confidence	FAO 2015, 2018b; FAO et al. 2018; Pradhan et al. 2013; World Bank 2018a,b
Reduced landslides and natural hazards	1–100 million people	Low confidence	Campbell 2015
Reduced pollution including acidification	Increase annual crop yields 30–135 Mt globally; feeds 100–450 million people	Low confidence	FAO 2018b; FAO et al. 2018; Pradhan et al. 2013; World Bank 2018a
Management of invasive species/encroachment	No global estimates	No evidence	
Restoration and reduced conversion of coastal wetlands	Very small negative impact but not quantified	Low confidence	
Restoration and reduced conversion of peatlands	Potential negative impact on 21–31 million people	Low confidence	Clark and Tilman 2017; FAO 2018b
Biodiversity conservation	No global estimates	No evidence	

Integrated response options based on land management specifically for CDR

The spreading of crushed minerals on land as part of enhanced weathering on nutrient-depleted soils can potentially increase crop yield by replenishing plant available silicon, potassium and other plant nutrients (Beerling et al. 2018), but there are no estimates in the literature reporting the potential magnitude of this effect on global food production.

Competition for land between bioenergy and food crops can lead to adverse side effects for food security. Many studies indicate that bioenergy could increase food prices (Calvin et al. 2014; Popp et al. 2017; Wise et al. 2009). Only three studies were found linking bioenergy to the population at risk of hunger; they estimate an increase in the population at risk of hunger of between 2 million and 150 million people (Table 6.49).

Table 6.49 summarises the impact on food security of response options specifically for CDR, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.49 | Effects on food security of response options specifically for CDR.

Integrated response option	Potential	Confidence	Citation
Enhanced weathering of minerals	No global estimates	No evidence	
Bioenergy and BECCS	Negative impact on up to 150 million people	Low confidence	Chapter 7; Chapter 7 SM Baldos and Hertel 2014; Fujimori et al. 2018

6.3.5.2 Integrated response options based on value chain management

In this section, the impacts on food security of integrated response options based on value chain management are assessed.

Integrated response options based on value chain management through demand management

Dietary change can free up agricultural land for additional production (Bajželj et al. 2014a; Stehfest et al. 2009; Tilman and Clark 2014) and reduce the risk of some diseases (Tilman and Clark 2014; Aleksandrowicz et al. 2016), with large positive impacts on food security (Table 6.50).

Kummu et al. (2012) estimate that an additional billion people could be fed if food waste was halved globally. This includes both post-harvest losses and retail and consumer waste. Measures such as improved food transport and distribution could also contribute to this waste reduction (Table 6.50).

While no studies quantified the effect of material substitution on food security, the effects are expected to be similar to reforestation and afforestation if the amount of material substitution leads to an increase in forest area.

Table 6.50 summarises the impact on food security of demand management options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.50 | Effects on food security of demand management options.

Integrated response option	Potential	Confidence	Citation
Dietary change	821 million people	High confidence	Aleksandrowicz et al. 2016; Tilman and Clark 2014
Reduced post-harvest losses	1000 million people	Medium confidence	Kummu et al. 2012
Reduced food waste (consumer or retailer)	700–1000 million people	Medium confidence	FAO 2018b; Kummu et al. 2012
Material substitution	No global estimates	No evidence	

Integrated response options based on value chain management through supply management

Since 810 million people are undernourished (FAO 2018b), this sets the maximum number of those who could potentially benefit from sustainable sourcing or better management of supply chains. Currently, however, only 1 million people are estimated to benefit from sustainable sourcing (Tayleur et al. 2017). For the others, food price spikes affect food security and health; there are clearly documented effects of stunting among young children as a result of the 2007/2008 food supply crisis (de Brauw 2011; Arndt et al. 2016; Brinkman et al. 2009; Darnton-Hill and Cogill 2010) with a 10% increase in wasting attributed to the crisis in South Asia (Vellakkal et al. 2015). There is conflicting evidence on the impacts of different food price stability options for supply chains, and little quantification (Byerlee et al. 2006; del Ninno et al. 2007; Alderman 2010; Braun et al. 2014). Reduction in staple food prices due to price stabilisation resulted in more expenditure on other foods and increased nutrition (e.g., oils, animal products), leading to a 10% reduction in malnutrition among children in one study (Torlesse et al. 2003). Comparison of two African countries shows that protectionist policies (food price controls) and safety nets to reduce price instability resulted in a 20% decrease in risk of malnutrition (Nandy et al. 2016). Models using policies for food aid and domestic food reserves to achieve food supply and price stability showed the most effectiveness of all options in achieving climate mitigation and food security goals (e.g., more effective than carbon taxes) as they did not exacerbate food insecurity and did not reduce ambitions for achieving temperature goals (Fujimori et al. 2019).

For urban food systems, increased food production in cities, combined with governance systems for distribution and access can improve food security, with a potential to produce 30% of food consumed in cities. The urban population in 2018 was 4.2 billion people, so 30% represents 1230 million people who could benefit in terms of food security from improved urban food systems (Table 6.51).

It is estimated that 500 million smallholder farmers depend on agricultural businesses in developing countries (World Bank 2017), which sets the maximum number of people who could benefit from improved efficiency and sustainability of food processing, retail and agri-food industries.

Up to 2500 million people could benefit from increased energy efficiency in agriculture, based on the estimated number of people worldwide lacking access to clean energy and instead relying on biomass fuels for their household energy needs (IEA 2014).

Table 6.51 summarises the impact on food security of supply management options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.51 | Effects on food security of supply management options.

Integrated response option	Potential	Confidence	Citation
Sustainable sourcing	>1 million people	Low confidence	Tayleur et al. 2017
Management of supply chains	>1 million people	Low confidence	FAO 2018b; Kummu et al. 2012
Enhanced urban food systems	Up to 1260 million people	Low confidence	Benis and Ferrão 2017; Padgham et al. 2014; Specht et al. 2014; Zeeuw and Drechsel 2015
Improved food processing and retailing	500 million people	Low confidence	World Bank 2017
Improved energy use in food systems	Up to 2500 million people	Low confidence	IEA 2014

6.3.5.3 Integrated response options based on risk management

In this section, the impacts on food security of integrated response options based on risk management are assessed.

Evidence in the USA indicates ambiguous trends between sprawl and food security: on the one hand, most urban expansion in the USA has primarily been on lands of low and moderate soil productivity with only 6% of total urban land on highly productive soil; on the other hand, highly productive soils have experienced the highest rate of conversion of any soil type (Nizeyimana et al. 2001). Specific types of agriculture are often practiced in urban-influenced fringes, such as fruits, vegetables, and poultry and eggs in the USA, the loss of which can have an impact on the types of nutritious foods available in urban areas (Francis et al. 2012). China is also concerned with food security implications of urban sprawl, and a loss of 30 Mt of grain production from 1998 to 2003 in eastern China was attributed to urbanisation (Chen 2007). However, overall global quantification has not been attempted.

Diversification is associated with increased welfare and incomes and decreased levels of poverty in several country studies (Arslan et al. 2018; Asfaw et al. 2018). These are likely to have large food security benefits (Barrett et al. 2001; Niehof 2004), but there is little global quantification.

Local seed use can provide considerable benefits for food security because of the increased ability of farmers to revive and strengthen local food systems (McMichael and Schneider 2011); studies have reported more diverse and healthy food in areas with strong food sovereignty networks (Coomes et al. 2015; Bisht et al. 2018). Women, in particular, may benefit from seed banks for low-value but nutritious crops (Patnaik et al. 2017). Many hundreds of millions of smallholders still rely on local seeds and they provide for many hundreds of millions of consumers (Altieri et al. 2012; McGuire and Sperling 2016). Therefore, keeping their ability to do so through seed sovereignty is important. However, there may be lower food yields from local and unimproved seeds, so the overall impact of local seed use on food security is ambiguous (McGuire and Sperling 2016).

Disaster risk management approaches can have important impacts on reducing food insecurity, and current warning systems for drought and storms currently reach over 100 million people. When these early warning systems can help farmers harvest crops in advance of impending weather events, or otherwise make agricultural decisions to prepare for adverse events, there are likely to be positive impacts on food security (Fakhruddin et al. 2015). Surveys with farmers reporting food insecurity from climate impacts have indicated their strong interest in having such early warning systems (Shisanya and Mafongoya 2016). Additionally, famine early warning systems have been successful in Sahelian Africa to alert authorities of impending food shortages so that food acquisition and transportation from outside the region can begin, potentially helping millions of people (Genesio et al. 2011; Hillbruner and Moloney 2012).

Risk-sharing instruments are often aimed at sharing food supplies and reducing risk, and thus are likely to have important, but unquantified, benefits for food security. Crop insurance, in particular, has generally led to (modest) expansions in cultivated land area and increased food production (Claassen et al. 2011a; Goodwin et al. 2004).

Table 6.52 summarises the impact on food security of risk management options, with confidence estimates based on the thresholds outlined in Table 6.53 in Section 6.3.6, and indicative (not exhaustive) references upon which the evidence in based.

Table 6.52 | Effects on food security of risk management options.

Integrated response option	Potential	Confidence	Citation
Management of urban sprawl	>1 million likely	Low confidence	Bren d'Amour et al. 2016; Chen 2017
Livelihood diversification	>100 million	Low confidence	Morton 2007
Use of local seeds	>100 million	Low confidence	Altieri et al. 2012
Disaster risk management	>100 million	Medium confidence	Genesio et al. 2011; Hillbruner and Moloney 2012
Risk-sharing instruments	>1 million likely	Low confidence	Claassen et al. 2011a; Goodwin et al. 2004

6.3.6 Summarising the potential of the integrated response options across mitigation, adaptation, desertification land degradation and food security

Using the quantification provided in Tables 6.13 to 6.52, the impacts are categorised as either positive or negative, and are designated as large, moderate and small, according to the criteria given in Table 6.53.[7]

Table 6.53 | Key for criteria used to define the magnitude of the impact of each integrated response option.

	Mitigation	Adaptation	Desertification	Land degradation	Food
Large positive	More than 3 $GtCO_2$-eq yr^{-1}	Positively impacts more than around 25 million people	Positively impacts more than around 3 million km^2	Positively impacts more than around 3 million km^2	Positively impacts more than around 100 million people
Moderate positive	0.3–3 $GtCO_2$-eq	1 million to 25 million	0.5–3 million km^2	0.5–3 million km^2	1 million to 100 million
Small positive	>0	Under 1 million	>0	>0	Under 1 million
Negligible	0	No effect	No effect	No effect	No effect
Small negative	<0	Under 1 million	<0	<0	Under 1 million
Moderate negative	–0.3 to –3 $GtCO_2$-eq	1 million to 25 million	0.5 to 3 million km^2	0.5 to 3 million km^2	1 million to 100 million
Large negative	More than –3 $GtCO_2$-eq yr^{-1}	Negatively impacts more than around 25 million people	Negatively impacts more than around 3 million km^2	Negatively impacts more than around 3 million km^2	Negatively impacts more than around 100 million people

Note: All numbers are for global scale; all values are for technical potential. For mitigation, the target is set at around the level of large single mitigation measure (about 1 GtC yr^{-1} = 3.67 $GtCO_2$-eq yr^{-1}) (Pacala and Socolow 2004), with a combined target to meet 100 $GtCO_2$ in 2100, to go from baseline to 2°C (Clarke et al. 2014). For adaptation, numbers are set relative to the about 5 million lives lost per year attributable to climate change and a carbon-based economy, with 0.4 million per year attributable directly to climate change. This amounts to 100 million lives predicted to be lost between 2010 and 2030 due to climate change and a carbon-based economy (DARA 2012), with the largest category representing 25% of this total. For desertification and land degradation, categories are set relative to the 10–60 million km^2 of currently degraded land (Gibbs and Salmon 2015) with the largest category representing 30% of the lower estimate. For food security, categories are set relative to the roughly 800 million people currently undernourished (HLPE 2017) with the largest category representing around 12.5% of this total.

Tables 6.54 to 6.61 summarise the potentials of the integrated response options across mitigation, adaptation, desertification, land degradation and food security. Cell colours correspond to the large, moderate and small impact categories shown in Table 6.53.

As seen in Tables 6.54 to 6.61, three response options across the 14 for which there are data for every land challenge: *increased food productivity*, *agroforestry* and *increased soil organic carbon content*, deliver large benefits across all five land challenges.

A further six response options: *improved cropland management*, *improved grazing land management*, *improved livestock management*, *agroforestry*, *fire management* and *reduced post-harvest losses*, deliver either large or moderate benefits for all land challenges.

Three additional response options: *dietary change*, *reduced food waste* and *reduced soil salinisation*, each missing data to assess global potential for just one of the land challenges, deliver large or moderate benefits to the four challenges for which there are global data.

[7] Note: 1) The response options often overlap, so are not additive. For example, increasing food productivity will involve changes to cropland, grazing land and livestock management, which in turn may include increasing soil carbon stocks. Therefore, the response options cannot be summed or regarded as entirely mutually exclusive interventions. 2) The efficacy of a response option for addressing the primary challenge for which it is implemented needs to be weighed against any co-benefits and adverse side effects for the other challenges. For example, if a response option has a major impact in addressing one challenge but results in relatively minor and manageable adverse side effects for another challenge, it may remain a powerful response option despite the adverse side effects, particularly if they can be minimised or managed. 3) Though the impacts of integrated response options have been quantified as far as possible in Section 6.3, there is no equivalence implied in terms of benefits or adverse side effects, either in number or in magnitude of the impact – that is, one benefit *does not equal* one adverse side effect. As a consequence (i) large benefits for one challenge might outweigh relatively minor adverse side effects in addressing another challenge, and (ii) some response options may deliver mostly benefits with few adverse side effects, but the benefits might be small in magnitude, that is, the response options do no harm, but present only minor co-benefits. A number of benefits and adverse side effects are context specific; the context specificity has been discussed in Section 6.2 and is further examined Section 6.4.5.1.

Eight response options: *increased food productivity, reforestation and forest restoration, afforestation, increased soil organic carbon content, enhanced mineral weathering, dietary change, reduced post-harvest losses*, and *reduced food waste*, have large mitigation potential (>3 $GtCO_2e\ yr^{-1}$) without adverse impacts on other challenges.

Sixteen response options: *increased food productivity, improved cropland management, agroforestry, agricultural diversification, forest management, increased soil organic carbon content, reduced landslides and natural hazards, restoration and reduced conversion of coastal wetlands, reduced post-harvest losses, sustainable sourcing, management of supply chains, improved food processing and retailing, improved energy use in food systems, livelihood diversification, use of local seeds,* and *disaster risk management*, have large adaptation potential at global scale (positively affecting more than 25 million people) without adverse side effects for other challenges.

Thirty-three of the 40 response options can be applied without requiring land-use change and limiting available land. A large number of response options do not require dedicated land, including several land management options, all value chain options, and all risk management options. Four options, in particular, could greatly increase competition for land if applied at scale: *afforestation, reforestation*, and land used to provide feedstock for *bioenergy (with or without BECCS)* and *biochar*, with three further options: *reduced grassland conversion to croplands, restoration and reduced conversion of peatlands,* and *restoration and reduced conversion of coastal wetlands* having smaller or variable impacts on competition for land. Other options such as *reduced deforestation and forest degradation*, restrict land conversion for other options and uses.

Some response options can be more effective when applied together – for example, *dietary change* and *waste reduction* expand the potential to apply other options by freeing as much as 25 Mkm^2 (4–25 Mkm^2 for dietary change; Alexander et al. 2016; Bajželj et al. 2014b; Stehfest et al. 2009; Tilman and Clark 2014 and 7 Mkm^2 for reduced food waste; Bajželj et al. 2014b).

In terms of the categories of response options, most agricultural land management response options (all except for reduced grassland conversion to cropland which potentially adversely affects food security), deliver benefits across the five land challenges (Table 6.54). Among the forest land management options, afforestation and reforestation have the potential to deliver large co-benefits across all land challenges except for food security, where these options provide a threat due to competition for land (Table 6.55). Among the soil-based response options, some global data are missing, but none except biochar shows any potential for negative impacts, with that potential negative impact arising from additional pressure on land if large quantities of biomass feedstock are required for biochar production (Table 6.56). Where global data exists, most response options in other/all ecosystems deliver benefits, except for a potential moderate negative impact on food security by restoring peatlands currently used for agriculture (Table 6.57). Of the two response options specifically targeted at CDR, there are missing data for enhanced weathering of minerals for three of the challenges, but large-scale bioenergy and BECCS show a potential large benefit for mitigation, but small to large adverse impacts on the other four land challenges (Table 6.58), mainly driven by increased pressure on land due to feedstock demand.

While data allow the impact of material substitution to be assessed only for mitigation, the three other demand-side response options: *dietary change*, *reduced post-harvest losses*, and *reduced food waste* provide large or moderate benefits across all challenges for which data exist (Table 6.59). Data is not available for any of the supply-side response options to assess the impact on more than three of the land challenges, but there are large to moderate benefits for all those for which data are available (Table 6.60). Data are not available to assess the impact of risk-management-based response options on all of the challenges, but there are small to large benefits for all of those for which data are available (Table 6.61).

Table 6.54 | Summary of direction and size of impact of land management options in agriculture on mitigation, adaptation, desertification, land degradation and food security.

Integrated response option	Mitigation	Adaptation	Desertification	Land degradation	Food security	Context and evidence base for magnitude of effect
Increased food productivity						These estimates assume that increased food production is implemented sustainably (e.g., through sustainable intensification: Garnett et al. 2013; Pretty et al. 2018) rather than through increasing external inputs, which can have a range of negative impacts. **Mitigation:** *Large benefits* (Table 6.13). **Adaptation:** *Large benefits* (Campbell et al. 2014) (Chapter 2 and Table 6.21). **Desertification:** *Large benefits* (Dai 20100 (Chapter 3 and Table 6.29). **Land degradation:** *Large benefits* (Clay et al. 1995) (Chapter 4 and Table 6.37). **Food security:** *Large benefits* (Godfray et al. 2010; Godfray and Garnett 2014; Tilman et al. 2011) (Chapter 5 and Table 6.45).
Improved cropland management						**Mitigation:** *Moderate benefits* by reducing GHG emissions and creating soil carbon sinks (Smith et al. 2008, 2014) (Chapter 2 and Table 6.13). **Adaptation:** *Large benefits* by improving the resilience of food crop production systems to future climate change (Porter et al. 2014) (Chapter 2 and Table 6.21). **Desertification:** *Large benefits* by improving sustainable use of land in dry areas (Bryan et al. 2009; Chen et al. 2010) (Chapter 3 and Table 6.29). **Land degradation:** *Large benefits* by forming a major component of sustainable land management (Labrière et al. 2015) (Chapter 4 and Table 6.37). **Food security:** *Large benefits* by improving agricultural productivity for food production (Porter et al. 2014) (Chapter 5 and Table 6.45).
Improved grazing land management						**Mitigation:** *Moderate benefits* by increasing soil carbon sinks and reducing GHG emissions (Herrero et al. 2016) (Chapter 2 and Table 6.13). **Adaptation:** *Moderate benefits* by improving the resilience of grazing lands to future climate change (Porter et al. 2014) (Chapter 2 and Table 6.21). **Desertification:** *Moderate benefits* by tackling overgrazing in dry areas to reduce desertification (Archer et al. 2011) (Chapter 3 and Table 6.29). **Land degradation:** *Large benefits* by optimising stocking density to reduce land degradation (Tighe et al. 2012) (Chapter 4, Table 6.37 and Table 6.45). **Food security:** *Large benefits* by improving livestock sector productivity to increase food production (Herrero et al. 2016) (Chapter 5 and Table 6.45).
Improved livestock management						**Mitigation:** *Moderate benefits* by reducing GHG emissions, particularly from enteric methane and manure management (Smith et al. 2008, 2014) (Chapter 2 and Table 6.13). **Adaptation:** *Moderate benefits* by improving resilience of livestock production systems to climate change (Porter et al. 2014) (Chapter 2 and Table 6.21). **Desertification:** *Moderate benefits* by tackling overgrazing in dry areas (Archer et al. 2011) (Chapter 3 and Table 6.29). **Land degradation:** *Large benefits* by reducing overstocking which can reduce land degradation (Tighe et al. 2012) (Chapter 4, Table 6.37 and Table 6.45). **Food security:** *Large benefits* by improving livestock sector productivity to increase food production (Herrero et al. 2016) (Chapter 5 and Table 6.45).
Agroforestry						**Mitigation:** *Large benefits* by increasing carbon sinks in vegetation and soils (Delgado 2010; Mbow et al. 2014a; Griscom et al. 2017) (Chapter 2 and Table 6.13). **Adaptation:** *Large benefits* by improving the resilience of agricultural lands to climate change (Mbow et al. 2014a) (Chapter 2 and Table 6.21). **Desertification:** *Large benefits* through, for example, providing perennial vegetation in dry areas (Nair et al. 2010; Lal 2001) (Chapter 3 and Table 6.29). **Land degradation:** *Large benefits* by stabilising soils through perennial vegetation (Narain et al. 1997; Lal 2001) (Chapter 4 and Table 6.37). **Food production:** *Large benefits* since well-planned agroforestry can enhance productivity (Bustamante et al. 2014; Sascha et al. 2017) (Chapter 5 and Table 6.45).
Agricultural diversification						Agricultural diversification is a collection of practices aimed at deriving more crops or products per unit of area (e.g., intercropping) or unit of time (e.g., double cropping, ratoon crops, etc.). **Mitigation:** *Limited benefits* (Table 6.13). **Adaptation:** *Large benefits* through improved household income (Pellegrini and Tasciotti 2014) (Table 6.21). **Desertification:** *Moderate benefits*, limited by global dryland cropped area (Table 6.29). **Land degradation:** *Large benefits* by reducing pressure on land (Lambin and Meyfroidt 2011) (Table 6.37). **Food security:** *Large benefits* for food security by provision of more diverse foods (Birthal et al. 2015; Massawe et al. 2016; Waha et al. 2018) (Chapter 5 and Table 6.45).
Reduced grassland conversion to cropland		ND				**Mitigation:** *Moderate benefits* by retaining soil carbon stocks that might otherwise be lost. Historical losses of soil carbon have been in the order of 500 $GtCO_2$ (Sanderman et al. 2017) (Table 6.13). Mean annual global cropland conversion rates (1961–2003) have been 0.36% per year (Krause et al. 2017), that is, around 47,000 $km^2\ yr^{-1}$ – so preventing conversion could potentially save moderate emissions of CO_2. **Adaptation:** No literature (Table 6.21). **Desertification:** *Limited benefits* by shifting from annual crops to permanent vegetation cover under grass in dry areas (Table 6.29) (Chapter 3). **Land degradation:** *Limited benefits* by shifting from annual crops to permanent vegetation cover under grass (Chapter 4 and Table 6.37). **Food security:** *Moderate negative impacts*, since more land is required to produce human food from livestock products on grassland than from crops on cropland, meaning that a shift to grassland could reduce total productivity and threaten food security (Clark and Tilman 2017) (Chapter 5 and Table 6.45).
Integrated water management						**Mitigation:** *Moderate benefits* by reducing GHG emissions mainly in cropland and rice cultivation (Smith et al. 2008, 2014) (Chapter 2 and Table 6.13). **Adaptation:** *Large benefits* by improving the resilience of food crop production systems to future climate change (Porter et al. 2014) (Chapter 2 and Table 6.21). **Desertification:** *Limited benefits* by improving sustainable use of land in dry areas (Chapter 3 and Table 6.29). **Land degradation:** *Limited benefits* by forming a major component of sustainable land and water management (Chapter 4 and Table 6.37). **Food security:** *Large benefits* by improving agricultural productivity for food production (Godfray and Garnett 2014; Tilman et al. 2011) (Chapter 5 and Table 6.45).

Large positive | Small positive | Small negative | Large negative
Moderate positive | Negligible/no effect | Moderate negative | Variable

Note: Cell colours correspond to the large, moderate and small categories shown in Table 6.53. ND = no data.

6

Table 6.55 | Summary of direction and size of impact of land management options in forests on mitigation, adaptation, desertification, land degradation and food security.

Integrated response option	Mitigation	Adaptation	Desertification	Land degradation	Food security	Context and evidence base for magnitude of effect
Forest management						**Mitigation:** *Moderate benefits* by conserving and enhancing carbon stocks in forests and long-lived products, through, for example, selective logging (Smith et al. 2014) (Table 6.14). **Adaptation:** *Large benefits*, including through improving ecosystem functionality and services, with mostly qualitative evidence at global scale and more robust estimates at regional level and local scale (Locatelli et al. 2015b) (Table 6.22). **Desertification and land degradation:** *Large benefits* by helping to stabilise land and regulate water and microclimate (Locatelli et al. 2015b) (Chapters 3 and 4, and Tables 6.30 and 6.38). **Food security:** *Moderate benefits* with mostly qualitative estimate at global level, by providing food to local communities, and diversify daily diets (Chapter 5 and Table 6.46).
Reduced deforestation and forest degradation						**Mitigation:** *Large benefits* by maintaining carbon stocks in forest ecosystems (Chapter 2 and Table 6.14). **Adaptation:** *Moderate benefits* at global scale when effect is cumulated until the end of the century; local scale, co-benefits between REDD+ and adaptation of local communities can be more substantial (Long 2013; Morita and Matsumoto 2018), even if often difficult to quantify and not explicitly acknowledged (McElwee et al. 2017a) (Table 6.22). **Desertification and land degradation:** *Large benefits* at global scale when effects are cumulated for at least 20 years, for example, through reduced soil erosion (Borrelli et al. 2017) (Tables 6.30 and 6.38). The uncertainty of these global estimates is high, while more robust qualitative and some quantitative estimates are available at regional level. **Food security:** *Small benefits;* difficult to quantify at global level (Chapter 5 and Table 6.46).
Reforestation and forest restoration						**Mitigation:** *Large benefits* by rebuilding the carbon stocks in forest ecosystems, although decreases in surface albedo can reduce the net climate benefits, particularly in areas affected by seasonal snow cover (Sonntag et al. 2016; Mahmood et al. 2014) (Chapter 2 and Table 6.14). **Adaptation:** *Large benefits* by provision of Nature's Contributions to People, including improving ecosystem functionality and services, providing microclimatic regulation for people and crops, wood and fodder as safety nets, soil erosion protection and soil fertility enhancement for agricultural resilience, coastal area protection, water and flood regulation (Locatelli et al. 2015b) (Table 6.22). **Desertification:** *Large benefits* through restoring forest ecosystems in dryland areas (Medugu et al. 2010; Salvati et al. 2014) (Chapter 3 and Table 6.30). **Land degradation:** *Large benefits* by re-establishment of perennial vegetation (Ellison et al. 2017) (Chapter 4 and Table 6.38). **Food security:** *Moderate negative impacts* due to potential competition for land for food production (Frank et al. 2017) (Chapter 5 and Table 6.46).
Afforestation						**Mitigation:** *Large benefits* for mitigation (Chapter 2 and Table 6.14), especially if it occurs in the tropics and in areas that are not significantly affected by seasonal snow cover. **Adaptation:** *Large benefits* on adaptation (Kongsager et al. 2016; Reyer et al. 2009) (Chapter 2 and Table 6.22). **Desertification:** *Large benefits* by providing perennial vegetation in dry areas to help control desertification (Medugu et al. 2010; Salvati et al. 2014) (Chapter 3 and Table 6.30). **Land degradation:** *Large benefits* by stabilising soils through perennial vegetation (Lal 2001) (Chapter 4 and Table 6.38). **Food security:** *Large negative impacts* due to competition for land for food production (Kreidenweis et al. 2016; Smith et al. 2013) (Chapter 5 and Table 6.46).

Large positive
Moderate positive
Small positive
Moderate negative
Large negative

Note: Cell colours correspond to the large, moderate and small categories shown in Table 6.53. ND = no data.

Table 6.56 | Summary of direction and size of impact of soil-based land management options on mitigation, adaptation, desertification, land degradation and food security.

Integrated response option	Mitigation	Adaptation	Desertification	Land degradation	Food security	Context and evidence base for magnitude of effect
Increased soil organic carbon content						**Mitigation:** *Large benefits* by creating soil carbon sinks (Table 6.15). **Adaptation:** *Large benefits* by improving resilience of food crop production systems to climate change (IPBES 2018) (Chapter 2 and Table 6.24). **Desertification:** *Large benefits* by improving soil health and sustainable use of land in dry areas (D'Odorico et al. 2013) (Chapter 3 and Table 6.31). **Land degradation:** *Large benefits* since it forms a major component of recommended practices for sustainable land management (Altieri and Nicholls 2017) (Chapter 4 and Table 6.39). **Food security:** *Large benefits* since it can increase yield and yield stability to enhance food production, though this is not always the case (Pan et al. 2009; Soussana et al. 2019; Hijbeek et al. 2017b; Schjønning et al. 2018) (Chapter 5 and Table 6.47).
Reduced soil erosion						**Mitigation:** *Large benefits or large negative impacts*, since the final fate of eroded material is still debated – for example, at the global level, it is debated whether it is a large source or a large sink (Hoffmann et al. 2013) (Chapter 2 and Table 6.15). **Adaptation:** *Large benefits* since soil erosion control prevents **desertification** (*large benefits*) and **land degradation** (*large benefits*), thereby improving the resilience of agriculture to climate change (Lal 1998; FAO and ITPS 2015) (Chapters 2, 3 and 4, and Tables 6.23, 6.30 and 6.39). **Food security:** *Large benefits* mainly through the preservation of crop productivity (Lal 1998) (Chapter 5 and Table 6.47).
Reduced soil salinisation	ND					Techniques to prevent and reverse soil salinisation include groundwater management by drainage systems and/or crop rotation and use of amendments to alleviate soil sodicity. **Mitigation:** There are no studies to quantify the global impacts (Table 6.15). **Adaptation:** *Moderate benefits* by allowing existing crop systems to be maintained, reducing the need to abandon land (Dagar et al. 2016; UNCTAD 2011) (Table 6.23). **Desertification** and **land degradation:** *Moderate benefits* since soil salinisation is a main driver of both desertification and land degradation (Rengasamy 2006; Dagar et al. 2016) (Chapters 3 and 4, and Tables 6.31 and 6.39). **Food security:** *Moderate benefits* by maintaining existing cropping systems and helping to close yield gaps in rainfed crops (Table 6.47).
Reduced soil compaction	ND		ND			Techniques to prevent and reverse soil compaction are based on the combination of suitable crop rotations, tillage and regulation of agricultural traffic (Hamza and Anderson 2005). **Mitigation:** The global mitigation potential has not been quantified (Chamen et al. 2015; Epron et al. 2016; Tullberg et al. 2018) (Table 6.15). **Adaptation:** *Limited benefits* by improving productivity but on relatively small global areas (Table 6.22). **Desertification:** no global data (Table 6.31). **Land degradation:** *Large benefits* since soil compaction is a main driver of land degradation (FAO and ITPS 2015) (Table 6.39). **Food security:** *Moderate benefits* by helping to close yield gaps where compaction is a limiting factor (Anderson and Peters 2016) (Table 6.47).
Biochar addition to soil		ND	ND			**Mitigation:** *Large benefits* by increasing recalcitrant carbon stocks in the soil (Smith 2016; Fuss et al. 2018; IPCC 2018) (Chapter 2 and Table 6.15). **Adaptation:** There are no global estimates of the impact of biochar on climate adaptation (Table 6.23). **Desertification:** There are no global estimates of the impact of biochar on desertification (Table 6.31). **Land degradation:** *Limited benefits* by improving the soil water-holding capacity, nutrient-use efficiency, and potentially ameliorating heavy metal pollution (Sohi 2012) (Table 6.39). **Food security:** *Limited benefits* by increasing crop yields in the tropics – though not in temperate regions (Jeffery et al. 2017) – but potentially *Large negative impacts* by creating additional pressure on land if large quantities of biomass feedstock are required for biochar production (Table 6.47).

Large positive
Moderate positive
Small positive
Large negative
Variable

Note: Cell colours correspond to the large, moderate and small categories shown in Table 6.53. ND = no data.

Table 6.57 | Summary of direction and size of impact of land management in all/other ecosystems on mitigation, adaptation, desertification, land degradation and food security.

Integrated response option	Mitigation	Adaptation	Desertification	Land degradation	Food security	Context and evidence base for magnitude of effect
Fire management						**Mitigation:** *Large benefits* by reduced size, severity and frequency of wildfires, thereby preventing emissions and preserving carbon stocks (Arora and Melton 2018) (Table 6.16, Chapter 2, and Cross-Chapter Box 3 in Chapter 2). **Adaptation:** *Moderate benefits* by reducing mortality attributable to landscape fire smoke exposure, fire management provides adaptation benefits (Doerr and Santín 2016; Johnston et al. 2012; Koplitz et al. 2016) (Table 6.24). **Desertification:** *Large benefits* since control of wildfires and long-term maintenance of tree stock density protects against soil erosion (Neary et al. 2009; Arora and Melton 2018) (Table 6.32). **Land degradation:** *Large benefits* by stabilising forest ecosystems (Neary et al. 2009; Arora and Melton 2018) (Table 6.40). **Food security:** *Moderate benefits* by maintaining forest food product availability and preventing fire expansion to agricultural land (FAO 2015; Keenan et al. 2015; FAO et al. 2018; Pradhan et al. 2013; World Bank 2018a, b) (Table 6.48).
Reduced landslides and natural hazards						**Mitigation:** The prevention of landslides and natural hazards benefits mitigation, but because of the limited impact on GHG emissions and eventual preservation of topsoil carbon stores, the impact is estimated to be small globally (IPCC AR5 WG2, Chapter 14) (Table 6.16). **Adaptation:** Provides structural/physical adaptations to climate change (IPCC AR5 WG2, Chapter 14) (Table 6.24). **Desertification:** Due to the small global areas affected within global drylands, the benefits for desertification control are limited (Chapter 3 and Table 6.32). **Land degradation:** Since landslides and natural hazards are among the most severe degradation processes, prevention will have a large positive impact on land degradation (FAO and ITPS 2015) (Chapter 4 and Table 6.40). **Food security:** In countries where mountain slopes are cropped for food, such as in the Pacific Islands (Campbell 2015), the management and prevention of landslides can deliver benefits for food security, though the global areas are limited (Table 6.48).
Reduced pollution including acidification						**Mitigation:** *Large benefits* since measures to reduce emissions of short-lived climate pollutants (SLCPs) can slow projected global mean warming (UNEP and WMO 2011), with early intervention providing 0.5°C cooling by 2050 (UNEP and WMO 2011) (Table 6.16). But *moderate negative impacts* are also possible since reduced reactive nitrogen deposition could decrease terrestrial carbon uptake (Table 6.16). **Adaptation:** *Moderate benefits* since controlling particulate matter ($PM_{2.5}$) and ozone improves human health (Anenberg et al. 2012) (Table 6.24). **Desertification:** *Moderate benefits* since salinisation, pollution and acidification are stressors for desertification (Oldeman et al. 1991) (Table 6.32). **Land degradation:** *Moderate benefits* since acid deposition is a significant driver of land degradation (Oldeman et al. 1991; Smith et al. 2015) (Table 6.40). **Food security:** *Large benefits* since ozone is harmful to crops, so measures to reduce air pollution would be expected to increase crop production (FAO 2018b; FAO et al. 2018; Shindell et al. 2012; World Bank 2018a) (Table 6.48).
Management of invasive species/ encroachment	ND	ND	ND	ND	ND	There is no literature that assesses the global potential of management of invasive species on **mitigation, adaptation, desertification, land degradation** or on **food security** (Tables 6.16, 6.24, 6.33, 6.40 and 6.48).
Restoration and reduced conversion of coastal wetlands						**Mitigation:** *Large benefits* since coastal wetland restoration and avoided coastal wetland impacts deliver moderate carbon sinks by 2030 (Griscom et al. 2017) (Table 6.16). **Adaptation:** *Large benefits* by providing a natural defence against coastal flooding and storm surges by dissipating wave energy, reducing erosion and by helping to stabilise shore sediments (Table 6.24). **Desertification:** There is likely *negligible impact* of coastal wetland restoration for prevention of desertification (Table 6.32). **Land degradation:** *Limited benefits* since large areas of global coastal wetlands are degraded (Lotze et al. 2006; Griscom et al. 2017) (Table 6.40). **Food security:** *Small benefits* to *small adverse impacts* since large areas of converted coastal wetlands are used for food production (e.g., mangroves converted for aquaculture), restoration could displace food production and damage local food supply, though mangrove restoration can also restore local fisheries (Naylor et al. 2000) (Table 6.48).
Restoration and reduced conversion of peatlands		ND				**Mitigation:** *Moderate benefits* since avoided peat impacts and peat restoration deliver moderate carbon sinks by 2030 (Griscom et al. 2017) (Table 6.16), though there can be increases in methane emissions after restoration (Jauhiainen et al. 2008). **Adaptation:** Likely to be benefits by regulating water flow and preventing downstream flooding (Munang et al. 2014) (Table 6.24), but the global potential has not been quantified. **Desertification:** No impact since peatlands occur in wet areas and deserts in dry areas. **Land degradation:** *Moderate benefits* since large areas of global peatlands are degraded (Griscom et al. 2017) (Table 6.40). **Food security:** *Moderate adverse impacts* since restoration of large areas of tropical peatlands and some northern peatlands that have been drained and cleared for food production, could displace food production and damage local food supply (Table 6.48).
Biodiversity conservation			ND	ND	ND	**Mitigation:** *Moderate benefits* from carbon sequestration in protected areas (Calvin et al. 2014) (Table 6.16). **Adaptation:** *Moderate benefits* – likely many millions benefit from the adaptation and resilience of local communities to climate change (Secretariat of the Convention on Biological Diversity 2008) (Table 6.24), though global potential is poorly quantified. **Desertification:** No global data (Table 6.32). **Land degradation:** No global data (Table 6.40). **Food security:** No global data (Table 6.48).

Large positive
Moderate positive
Small positive
Moderate negative
Variable
Negligible/no effect

Note: Cell colours correspond to the large, moderate and small categories shown in Table 6.53. ND = no data.

Table 6.58 | Summary of direction and size of impact of land management options specifically for CDR on mitigation, adaptation, desertification, land degradation and food security.

Integrated response option	Mitigation	Adaptation	Desertification	Land degradation	Food security	Context and evidence base for magnitude of effect
Enhanced weathering of minerals		ND	ND		ND	**Mitigation:** *Moderate to large benefits* by removing atmospheric CO_2 (Table 6.17; Lenton 2010; Smith et al. 2016a; Taylor et al. 2016). **Adaptation:** There is no literature to assess the global impacts of enhanced mineral weathering on adaptation (Table 6.25) nor on **desertification** (Table 6.33). **Land degradation:** *Limited benefits* expected since ground minerals can increase pH where acidification is the driver of degradation (Table 6.41; Taylor et al. 2016). **Food security:** Though there may be co-benefits for food production (Beerling et al. 2018), these have not been quantified globally (Table 6.49).
Bioenergy and BECCS						**Mitigation:** *Large benefits* of large-scale bioenergy and BECCS by potential to remove large quantities of CO_2 from the atmosphere (Table 6.17). **Adaptation:** *Limited adverse impacts* of large-scale bioenergy and BECCS by increasing pressure on land (Table 6.25). **Desertification:** Up to 15 million km^2 of additional land is required in 2100 in 2°C scenarios, which will increase pressure for desertification and land degradation (Sections 6.3.3.1 and 6.3.4.1). This defines the maximum area potentially impacted, though the actual area affected by this additional pressure is not easily quantified. **Land degradation:** Up to 15 million km^2 of additional land is required in 2100 in 2°C scenarios, which will increase pressure for desertification and land degradation (Sections 6.3.3.1; 6.3.4.1). This defines the maximum area potentially impacted, though the actual area affected by this additional pressure is not easily quantified. **Food security:** *Large adverse impacts* of large-scale bioenergy and BECCS through increased competition for land for food (Table 6.49). These potentials and effects assume large areas of bioenergy crops, resulting in large mitigation potentials (i.e., >3 $GtCO_2\ yr^{-1}$). The sign and magnitude of the effects of bioenergy and BECCS depends on the scale of deployment, the type of bioenergy feedstock, which other response options are included, and where bioenergy is grown (including prior land use and indirect land-use change emissions). For example, limiting bioenergy production to marginal lands or abandoned cropland would have negligible effects on biodiversity, food security, and potentially small co-benefits for land degradation; however, the benefits for mitigation would also be smaller (Cross-Chapter Box 7 in this chapter, and Table 6.13).

Large positive Small positive Small negative Large negative

Note: Cell colours correspond to the large, moderate and small categories shown in Table 6.53. ND = no data.

Table 6.59 | Summary of direction and size of impact of demand management options on mitigation, adaptation, desertification, land degradation and food security.

Integrated response option	Mitigation	Adaptation	Desertification	Land degradation	Food security	Context and evidence base for magnitude of effect
Dietary change		ND				**Mitigation:** *Large benefits* for mitigation by greatly reducing GHG emissions (Chapter 5 and Table 6.18). **Adaptation:** While it would be expected to help with adaptation by reducing agricultural land area, there are no studies providing global quantifications (Table 6.26). **Desertification:** Potential *moderate benefits* by decreasing pressure on land – restricted by relatively limited global area (Table 6.34). **Land degradation:** *Large benefits* by decreasing pressure on land (Table 6.42). **Food security:** Large benefits by decreasing competition for land, allowing more food to be produced from less land (Table 6.50).
Reduced post-harvest losses						**Mitigation:** *Large benefits* by reducing food sector GHG emissions and reducing the area required to produce the same quantity of food (Table 6.18), though increased use of refrigeration could increase emissions from energy use. **Adaptation:** *Large benefits* by reducing pressure on land (Table 6.26). **Desertification** and **land degradation:** *Moderate benefits* for both by reducing pressure on land (Table 6.34 and Table 6.42). **Food security:** *Large benefits* since most of the food wasted in developing countries arises from post-harvest losses (Ritzema et al. 2017) (Chapter 5 and Table 6.50).
Reduced food waste (consumer or retailer)		ND				**Mitigation:** *Large benefits* by reducing food sector GHG emissions and reducing the area required to produce the same quantity of food (Table 6.18). **Adaptation:** While it would be expected to help with adaptation by reducing agricultural land area, there are no studies quantifying global adaptation impacts (Table 6.26). **Desertification:** *Moderate benefits* by reducing pressure on land (Table 6.34). **Land degradation:** *Large benefits* by reducing pressure on land (Table 6.42). **Food security:** *Large benefits* since 30% of all food produced globally is wasted (Kummu et al. 2012) (Table 6.50).
Material substitution		ND	ND	ND	ND	**Mitigation:** *Moderate benefits* through long-lived carbon storage, and by substitution of materials with higher embedded GHG emissions (Table 6.18). No global studies available to assess the quantitative impact on **adaptation, desertification, land degradation** or **food security** (Tables 6.26, 6.34, 6.42 and 6.50).

Large positive Moderate positive

Note: Cell colours correspond to the large, moderate and small categories shown in Table 6.53. ND = no data.

Table 6.60 | Summary of direction and size of impact of supply management options on mitigation, adaptation, desertification, land degradation and food security.

Integrated response option	Mitigation	Adaptation	Desertification	Land degradation	Food security	Context and evidence base for magnitude of effect
Sustainable sourcing	ND	Moderate positive	ND	Large positive	Moderate positive	**Mitigation:** No studies available to assess the global impact (Table 6.19). **Adaptation:** *Moderate benefits* by diversifying and increasing flexibility in the food system to climate stressors and shocks while simultaneously creating economic alternatives for the poor (thereby strengthening adaptive capacity) and lowering expenditures of food processors and retailers by reducing losses (Muller et al. 2017) (Chapter 5 and Table 6.27). **Desertification:** No studies available to assess the global impact (Table 6.35 and Table 6.43). **Land degradation:** Potentially *large benefits*, as over 4 Mkm^2 is currently certified for sustainable forest production, which could increase in future (Table 6.44). **Food security:** *Moderate benefits* by diversifying markets and developing value-added products in the food supply system, by increasing its economic performance and revenues to local farmers (Reidsma et al. 2010), by strengthening the capacity of food production chains to adapt to future markets and to improve income of smallholder farmers (Murthy and Madhava Naidu 2012) (Chapter 5 and Table 6.51). It may also provide more direct links between producers and consumers.
Management of supply chains	ND	Large positive	ND	ND	Moderate positive	**Mitigation:** There are no studies assessing the mitigation potential globally (Table 6.19). **Adaptation:** *Large benefits* by improving resilience to price increases or reducing volatility of production (Fafchamps et al. 1998; Haggblade et al. 2017) (Table 6.27). **Desertification** and **land degradation:** No studies assessing global potential (Tables 6.35 and 6.43). **Food security:** *Moderate benefits* through helping to manage food price increases and volatility (Vellakkal et al. 2015; Arndt et al. 2016) (Table 6.51).
Enhanced urban food systems	ND	ND	ND	ND	Large positive	There are no studies that assess the global potential to contribute to **mitigation, adaptation, desertification** or **land degradation** (Tables 6.19, 6.27, 6.35 and 6.43). **Food security:** *Large benefits* by increasing food access to urban dwellers and shortening of supply chains (Chappell et al. 2016) (Chapter 5 and Table 6.51).
Improved food processing and retailing	Moderate positive	Large positive	ND	ND	Large positive	**Mitigation:** *Moderate benefits* through reduced energy consumption, climate-friendly foods and reduced GHG emissions from transportation (Avetisyan et al. 2014), waste (Porter et al. 2016), and energy use (Mohammadi et al. 2014; Song et al. 2017) (Table 6.19). **Adaptation:** Large benefits among poor farmers through reduced costs and improved resilience (Table 6.27). **Desertification** and **land degradation:** There are no studies assessing global potential (Tables 6.35 and Table 6.43). **Food security:** *Large benefits* by supporting healthier diets and reducing food loss and waste (Garnett 2011) (Chapter 5 and Table 6.51).
Improved energy use in food systems	Moderate positive	Large positive	ND	ND	Large positive	**Mitigation:** *Moderate benefits* by reducing GHG emissions through decreasing use of fossil fuels and energy-intensive products, though the emission reduction is not accounted for in the agriculture, forestry and other land-use (AFOLU) sector (Smith et al. 2014; IPCC AR5 WG3 Chapter 11) (Table 6.19). **Adaptation:** *Large benefits* for small farmers by reducing costs and increasing their resilience to climate change (Table 6.27). **Desertification** and **land degradation:** There are no studies assessing global potential (Tables 6.35 and 6.43). **Food security:** *Large benefits*, largely by improving efficiency for 2.5 million people still using traditional biomass for energy (Chapter 5 and Table 6.51).

Large positive Moderate positive

Note: Cell colours correspond to the large, moderate and small categories shown in Table 6.53. ND = no data.

6

Table 6.61 | Summary of direction and size of impact of risk management options on mitigation, adaptation, desertification, land degradation and food security.

Integrated response option	Mitigation	Adaptation	Desertification	Land degradation	Food security	Context and evidence base for magnitude of effect
Management of urban sprawl	ND					**Mitigation:** There are no studies assessing the global potential (Table 6.20). **Adaptation:** *Moderate benefits* – though poorly quantified globally, likely to affect many millions of people (Table 6.28). **Desertification:** *Limited benefits* – though poorly quantified globally, 5000 km^2 is at risk from urban sprawl in Spain alone (Table 6.36). **Land degradation:** *Limited benefits* – though poorly quantified globally, urban sprawl effects millions of ha of land (Table 6.44). **Food security:** *Moderate benefits* estimated from impacts on food supply in models (Bren d'Amour et al. 2016) (Table 6.52).
Livelihood diversification	ND					**Mitigation:** There are no studies assessing the global potential (Table 6.20). **Adaptation:** *Large benefits* through helping households to buffer income fluctuations and providing a broader range of options for the future (Table 6.28; Ahmed and Stepp 2016; Thornton and Herrero 2014). **Desertification:** There are no studies assessing the global potential, although there are anecdotal reports of *limited benefits* from improved land management resulting from diversification (Batterbury 2001; Herrmann and Hutchinson 2005; Stringer et al. 2009) (Table 6.36). **Land degradation:** *Limited benefits*, for example, improved land-use mosaics (Palacios et al. 2013), larger-scale adoption in China's Sloping Land Conversion Program to diversify income and reduce degradation has impacted on 0.1 Mkm^2 (Liu and Lan 2015) (Table 6.44). **Food security:** *Large benefits* since many of the world's 700 million smallholders practice diversification, helping to provide economic access to food (Morton 2007) (Table 6.52).
Use of local seeds	ND		ND	ND		**Mitigation:** There are no studies assessing the global potential (Table 6.19). **Adaptation:** *Large benefits* given that 60 to 100% of seeds used in various countries of the global South are likely local farmer-bred (non-commercial) seed, and moving to the use of commercial seed would increase costs considerably for these farmers. Seed networks and banks protect local agrobiodiversity and landraces, which are important to facilitate adaptation, and can provide crucial lifelines when crop harvests fail (Louwaars 2002; Howard 2015; Coomes et al. 2015; Van Niekerk and Wynberg 2017; Vasconcelos et al. 2013; Reisman 2017) (Table 6.28). **Desertification** and **land degradation:** There are no studies assessing global potential (Tables 6.36 and Table 6.44). **Food security:** *Large benefits* since local seeds increase the ability of farmers to revive and strengthen local food systems; several studies have reported more diverse and healthy food in areas with strong food sovereignty networks (Coomes et al. 2015; Bisht et al. 2018) (Table 6.52).
Disaster risk management	ND		ND	ND		**Mitigation:** There are no studies to assess the global mitigation potential of different Disaster Risk Management (DRM) approaches (Table 6.19). **Adaptation:** *Large benefits* due to widespread use of early warning systems that reach hundreds of millions (Hillbruner and Moloney 2012; Mahmud and Prowse 2012; Birkmann et al. 2015) (Table 6.28). **Desertification** and **land degradation**. There are no studies assessing the global potential (Tables 6.36 and Table 6.44). **Food security:** *Moderate benefits* by helping farmers to harvest crops in advance of impending weather events, or otherwise to make agricultural decisions to prepare for adverse events (Fakhruddin et al. 2015; Genesio et al. 2011; Hillbruner and Moloney 2012) (Table 6.52).
Risk-sharing instruments			ND			**Mitigation:** *Variable impacts* – poor global coverage in the literature, though studies from the US suggest a small increase in emissions from crop insurance and likely benefits from other risk-sharing instruments (Table 6.20). **Adaptation:** *Moderate benefits* by buffering and transferring weather risk, saving farmers the cost of crop losses. However, overly subsidised insurance can undermine the market's role in pricing risks and thus depress more rapid adaptation strategies (Meze-Hausken et al. 2009; Skees and Collier 2012; Jaworski 2016) (Table 6.28). **Desertification:** The impacts of risk-sharing globally have not been quantified (Table 6.36). **Land degradation:** *Variable impacts* as evidence suggests that subsidised insurance in particular can increase crop production in marginal lands, and reforming this would lead to benefits (Table 6.44). **Food security:** *Small to moderate benefits* for food security, as risk-sharing often promotes food-supply sharing (Table 6.52).

Large positive | Moderate positive | Small positive | Variable

Note: Cell colours correspond to the large, moderate and small categories shown in Table 6.53. ND = no data.

6.4 Managing interactions and interlinkages

Having assessed the potential of each response option for contributing to addressing mitigation, adaptation, desertification, land degradation and food security in Section 6.3, this section assesses the feasibility of each response option with respect to cost, barriers, and issues of saturation and reversibility (Section 6.4.1), before assessing the sensitivity of the response options to future climate change (Section 6.4.2) and examining the contribution of each response option to ecosystem services (classified according to Nature's Contribution to People (IPBES 2018), and to sustainable development (assessed against the UN SDGs) (6.4.3). Section 6.4.4 examines opportunities for implementation of integrated response options, paving the way to potential policies examined in Chapter 7, before the consequences of delayed action are assessed in Section 6.4.5.

6.4.1 Feasibility of the integrated response options with respect to costs, barriers, saturation and reversibility

For each of the response options, Tables 6.62–6.69 summarise the feasibility with respect to saturation and reversibility and cost, technological, institutional, socio-cultural and environmental and geophysical barriers (the same barrier categories used in SR15).

Many land management options face issues of saturation and reversibility; however, these are not of concern for the value chain and risk management options. Reversibility is an issue for all options that increase terrestrial carbon stock, either through increased soil carbon or changes in land cover (e.g., reforestation, afforestation), since future changes in climate or land cover could result in reduced carbon storage (Smith 2013). In addition, the benefits of options that improve land management (e.g., improved cropland management, improved grazing management) will cease if the practice is halted, reversing any potential benefits.

The cost of the response options varies substantially, with some options having relatively low costs (e.g., the cost of agroforestry is less than 10 USD tCO_2e^{-1}) while others have much higher costs (e.g., the cost of BECCS could be as much as 250 USD tCO_2e^{-1}). In addition to cost, other economic barriers may prevent implementation; for example, agroforestry is a low-cost option (Smith et al. 2014), but lack of reliable financial support could be a barrier (Hernandez-Morcillo et al. 2018). Additionally, there are a number of reasons why even no-cost options are not adopted, including risk aversion, lack of information, market structure, externalities, and policies (Jaffe 2019).

Some of the response options have technological barriers that may limit their wide-scale application in the near term. For example, BECCS has only been implemented at small-scale demonstration facilities (Kemper 2015); challenges exist with upscaling these options to the levels discussed in this chapter.

Many response options have institutional and socio-cultural barriers. Institutional barriers include governance, financial incentives and financial resources. For example, the management of supply chains includes challenges related to political will within trade regimes, economic laissez-faire policies that discourage interventions in markets, and the difficulties of coordination across economic sectors (Poulton et al. 2006; Cohen et al. 2009; Gilbert 2012). Implementation of other options, for example, BECCS, is limited by the absence of financial incentives.

Options like dietary change face socio-cultural barriers; while diets have changed in the past, they are deeply culturally embedded and behaviour change is extremely difficult to effect, even when health benefits are well known (Macdiarmid et al. 2018). For some options, the specific barrier is dependent on the region. For example, barriers to reducing food waste in industrialised countries include inconvenience, lack of financial incentives, lack of public awareness, and low prioritisation (Kummu et al. 2012; Graham-Rowe et al. 2014). Barriers in developing countries include reliability of transportation networks, market reliability, education, technology, capacity, and infrastructure (Kummu et al. 2012).

Table 6.62 | Feasibility of land management response options in agriculture, considering cost, technological, institutional, socio-cultural and environmental and geophysical barriers and saturation and reversibility. See also Appendix.

Response option	Saturation	Reversibility	Cost	Technological	Institutional	Socio-cultural	Environmental and geophysical	Context and sources
Increased food productivity								**Biophysical:** Only if limited by climatic and environmental factors. (Barnes and Thomson 2014; Martin et al. 2015a; Olesen and Bindi 2002; Pretty and Bharucha 2014; Schut et al. 2016.)
Improved cropland management								**Institutional:** Only in some regions (e.g., poor sustainability frameworks). **(**Bryan et al. 2009; Bustamante et al. 2014; Madlener et al. 2006; Reichardt et al. 2009; Roesch-McNally et al. 2017; Singh and Verma 2007; Smith et al. 2008, 2014.)
Improved grazing land management								**Institutional:** Only in some regions (e.g., need for extension services). **(**Herrero et al. 2016; McKinsey and Company 2009; Ndoro et al. 2014; Singh and Verma 2007; Smith et al. 2008, 2015.)
Improved livestock management								**Economic:** Improved productivity is cost negative, but others (e.g., dietary additives) are expensive. **Institutional:** Only in some regions (e.g., need for extension services). **(**Beauchemin et al. 2008; Herrero et al. 2016; McKinsey and Company 2009; Rojas-Downing et al. 2017; Smith et al. 2008; Thornton et al. 2009; Ndoro et al. 2014.)
Agroforestry								**Economic:** Low cost but may lack reliable financial support. **Institutional:** only in some regions (e.g., seed availability). (Lillesø et al. 2011; Meijer et al. 2015; Sileshi et al. 2008; Smith et al. 2007, 2014.)
Agricultural diversification								More support from extension services, access to inputs and markets, economic incentives for producing a certain crop or livestock product, research and investments focused on adapted varieties and climatic resilient systems, a combination of agricultural and non-agricultural activities (e.g., off-farm jobs) are all important interventions aimed at overcoming barriers to agricultural diversification. (Ahmed and Stepp 2016; Barnes et al. 2015; Barnett and Palutikof 2015; Martin and Lorenzen 2016; Roesch-McNally et al. 2016; Waha et al. 2018.)
Reduced grassland conversion to cropland								**Economic:** Avoiding conversion is low cost, but there may be significant opportunity costs associated with foregone production of crops. **Institutional:** only in some regions (e.g., poor governance to prevent conversion.)
Integrated water management								**Institutional:** Effective implementation is dependent on the adoption of a combination of 'hard', infrastructural, and 'soft' institutional measures. **Socio-cultural:** Education can be a barrier and some strategies (e.g., site-specific water management, drip irrigation) can be expensive. Cultural/behavioural barriers are likely to be small. (Dresner et al. 2015; Erwin 2009; Lotze et al. 2006; Thornton et al. 2009.)

Saturation and reversibility

- Not important
- A concern

Cost

- Low cost (<10 USD tCO_2e^{-1} or <20 USD ha^{-1})
- Medium cost (10–100 USD tCO_2e^{-1} or <20-200 USD ha^{-1})
- High cost (>100 USD tCO_2e^{-1} or 200 USD ha^{-1})

Technological, institutional, socio-cultural and environmental and geophysical barriers

- High current feasibility (no barriers)
- Medium current feasibility (moderate barriers)
- Low current feasibility (large barriers)
- Variable barriers

Note: The cost thresholds in USD tCO_2e^{-1} are from Griscom et al. (2017); thresholds in USD ha^{-1} are chosen to be comparable, but precise conversions will depend on the response option.

6

Table 6.63 | Feasibility of land management response options in forests, considering cost, technological, institutional, socio-cultural and environmental and geophysical barriers and saturation and reversibility. See also Appendix.

Response option	Saturation	Reversibility	Cost	Technological	Institutional	Socio-cultural	Environmental and geophysical	Context and sources
Forest management								Seidl et al. 2014
Reduced deforestation and forest degradation								**Economic:** Requires transaction and administration costs Busch and Engelmann 2017; Kindermann et al. 2008; Overmars et al. 2014
Reforestation and forest restoration								Strengers et al. 2008
Afforestation								Medugu et al. 2010; Kreidenweis et al. 2016

Note: See note for Table 6.62.

Table 6.64 | Feasibility of land management response options for soils, considering cost, technological, institutional, socio-cultural and environmental and geophysical barriers and saturation and reversibility. See also Appendix.

Response option	Saturation	Reversibility	Cost	Technological	Institutional	Socio-cultural	Environmental and geophysical	Context and sources
Increased soil organic carbon content								**Institutional:** Only in some regions (e.g., lack of institutional capacity). (Smith et al. 2008; McKinsey and Company 2009; Baveye et al. 2018; Bustamante et al. 2014; Reichardt et al. 2009; Smith 2004; Smith et al. 2007; Wollenberg et al. 2016).
Reduced soil erosion								Haregeweyn et al. 2015
Reduced soil salinisation								Barriers depend on how salinisation and sodification are implemented. (Bhattacharyya et al. 2015; CGIAR 2016; Dagar et al. 2016; Evans and Sadler 2008; Greene et al. 2016; Machado and Serralheiro 2017.)
Reduced soil compaction								Antille et al. 2016; Chamen et al. 2015
Biochar addition to soil								Saturation and reversibility issues lower than for soil organic carbon. **Economic:** In general, biochar has high costs. However, a small amount of biochar potential could be available at negative cost, and some at low cost, depending on markets for the biochar as a soil amendment. **Institutional:** Only in some regions (e.g., lack of quality standards). (Dickinson et al. 2014; Guo et al. 2016; Meyer et al. 2011; Shackley et al. 2011; Woolf et al. 2010) (Chapter 4.)

Saturation and reversibility

- Not important
- A concern

Cost

- Low cost (<10 USD tCO_2e^{-1} or <20 USD ha^{-1})
- Medium cost (10–100 USD tCO_2e^{-1} or <20-200 USD ha^{-1})
- High cost (>100 USD tCO_2e^{-1} or 200 USD ha^{-1})

Technological, institutional, socio-cultural and environmental and geophysical barriers

- High current feasibility (no barriers)
- Medium current feasibility (moderate barriers)
- Low current feasibility (large barriers)
- Variable barriers

Note: See note for Table 6.62.

Table 6.65 | Feasibility of land management response options in any/other ecosystems, considering cost, technological, institutional, socio-cultural and environmental and geophysical barriers and saturation and reversibility. See also Appendix.

Response option	Saturation	Reversibility	Cost	Technological	Institutional	Socio-cultural	Environmental and geophysical	Context and sources
Fire management								**Economic:** The cost of its implementation is moderate, since it requires constant maintenance, and can be excessive for some local communities. (Freeman et al. 2017; Hurteau et al. 2014; North et al. 2015.)
Reduced landslides and natural hazards								Gill and Malamud 2017; Maes et al. 2017; Noble et al. 2014
Reduced pollution including acidification								Begum et al. 2011; Shah et al. 2018; Yamineva and Romppanen 2017; WMO 2015
Management of invasive species/ encroachment								**Technological:** In the case of natural enemies. **Socio-cultural:** Education can be a barrier, where populations are unaware of the damage caused by the invasive species, but cultural/ behavioural barriers are likely to be small. **Institutional:** Where agricultural extension and advice services are poorly developed. **Source:** Dresner et al. 2015
Restoration and reduced conversion of coastal wetlands								**Economic:** Can be cost-effective at scale. **Institutional:** Only in some regions (e.g., poor governance of wetland use). **Socio-cultural:** Educational barriers (e.g., lack of knowledge of impact of wetland conversion), though cultural/behavioural barriers are likely to be small. (Erwin 2009; Lotze et al. 2006.)
Restoration and reduced conversion of peatlands								**Institutional:** Only in some regions (e.g., lack of inputs). (Bonn et al. 2014; Worrall et al. 2009.)
Biodiversity conservation								**Economic:** While protected areas and other forms of biodiversity conservation can be cost-effective, they are often underfunded relative to needs. **Institutional:** There have been challenges in getting systematic conservation planning to happen, due to institutional fragmentation and overlapping mandates. **Socio-cultural:** Despite the fact that biodiversity conservation may provide co-benefits, such as water or carbon protection, local populations often have had social and cultural conflicts with protected areas and other forms of exclusionary biodiversity conservation that are imposed in a top-down fashion or which restrict livelihood options. (Emerton et al. 2006; Hill et al. 2015; Langford et al. 2011; Larsen et al. 2012; Schleicher 2018; Wei et al. 2018; Wilkie et al. 2001.)

Note: See note for Table 6.62.

Table 6.66 | Feasibility of land management response options specifically for carbon dioxide removal (CDR), considering cost, technological, institutional, socio-cultural and environmental and geophysical barriers and saturation and reversibility. See also Appendix.

Response option	Saturation	Reversibility	Cost	Technological	Institutional	Socio-cultural	Environmental and geophysical	Context and sources
Enhanced weathering of minerals								Permanence not an issue on the decadal timescales. **Institutional:** Only in some regions (e.g., lack of infrastructure for this new technology). **Socio-cultural:** Could occur in some regions, for example, due to minerals lying under undisturbed natural areas where mining might generate public acceptance issues. (Renforth et al. 2012; Smith et al. 2016a; Taylor et al. 2016.)
Bioenergy and BECCS								**Economic:** While most estimates indicate the cost of BECCS as less than 200 USD tCO_2^{-1}, there is significant uncertainty. **Technological:** While there are a few small BECCS demonstration facilities, BECCS has not been implemented at scale. (IPCC 2018; Chapter 7; Kemper 2015; Sanchez and Kammen 2016; Vaughan and Gough 2016.)

Note: See note for Table 6.62.

Table 6.67 | Feasibility of demand management response options, considering economic, technological, institutional, socio-cultural and environmental and geophysical barriers and saturation and reversibility. See also Appendix.

Response option	Saturation	Reversibility	Cost	Technological	Institutional	Socio-cultural	Environmental and geophysical	Context and sources
Dietary change								**Institutional:** Only in some regions (e.g., poorly developed dietary health advice). (Hearn et al. 1998; Lock et al. 2005; Macdiarmid et al. 2018; Wardle et al. 2000).
Reduced post-harvest losses								
Reduced food waste (consumer or retailer)								Specific barriers differ between developed and developing countries. (Diaz-Ruiz et al. 2018; Graham-Rowe et al. 2014; Kummu et al. 2012.)
Material substitution								Gustavsson et al. 2006; Ramage et al. 2017

Note: See note for Table 6.62.

Table 6.68 | Feasibility of supply management response options, considering cost, technological, institutional, socio-cultural and environmental and geophysical barriers and saturation and reversibility. See also Appendix.

Response option	Saturation	Reversibility	Cost	Technological	Institutional	Socio-cultural	Environmental and geophysical	Context and sources
Sustainable sourcing								**Economic:** The cost of certification and sustainable sourcing can lead to higher production costs. **Institutional:** There are some barriers to adopting sustainable sourcing in terms of getting governments on board with market-based policies. **Socio-cultural:** Barriers include consumers unfamiliar with sustainably sourced goods. (Capone et al. 2014; Ingram et al. 2016.)
Management of supply chains								**Economic:** Supply chain management and management of price volatility faces challenges from businesses in terms of economic costs of change. **Technological:** Barriers like supply chain tracking. **Institutional:** Barriers like political will against government action in markets. (Cohen et al. 2009; Gilbert 2012; Poulton et al. 2006.)
Enhanced urban food systems								
Improved food processing and retailing								**Economic:** The implementation of strategies to improve the efficiency and sustainability of retail and agri-food industries can be expensive. **Institutional:** Successful implementation is dependent on organisational capacity, the agility and flexibility of business strategies, the strengthening of public-private policies and effectiveness of supply-chain governance.
Improved energy use in food systems								Baudron et al. 2015; Vlontzos et al. 2014

Saturation and reversibility

- Not important
- A concern

Cost

- Low cost (<10 USD tCO_2e^{-1} or <20 USD ha^{-1})
- Medium cost (10–100 USD tCO_2e^{-1} or <20-200 USD ha^{-1})
- High cost (>100 USD tCO_2e^{-1} or 200 USD ha^{-1})

Technological, institutional, socio-cultural and environmental and geophysical barriers

- High current feasibility (no barriers)
- Medium current feasibility (moderate barriers)
- Low current feasibility (large barriers)
- Variable barriers

Note: See note for Table 6.62.

Table 6.69 | Feasibility of risk management response options, considering cost, technological, institutional, socio-cultural and environmental and geophysical barriers and saturation and reversibility. See also Appendix.

Response option	Saturation	Reversibility	Cost	Technological	Institutional	Socio-cultural	Environmental and geophysical	Context and sources
Management of urban sprawl								There are economic and political forces that benefit from less-regulated urban development. (Tan et al. 2009.)
Livelihood diversification								**Economic:** Expanded diversification can cost additional financial resources. **Socio-cultural:** Problems with adoption of new or unfamiliar crops and livelihoods. (Ahmed and Stepp 2016; Berman et al. 2012; Ngigi et al. 2017.)
Use of local seeds								**Economic:** Local seeds are highly cost effective, and do not require new technology. **Institutional:** Barriers from agronomy departments and businesses promoting commercial seeds. **Socio-cultural:** Preferences for some non-local seed sourced crops. (Reisman 2017; Timmermann and Robaey 2016.)
Disaster risk management								**Economic:** Disaster risk management (DRM) systems can be initially costly, but usually pay for themselves over time. **Institutional:** Some barriers in terms of getting initial support behind new systems. (Birkmann et al. 2015; Hallegatte 2012.)
Risk-sharing instruments								There are few barriers to risk-sharing instruments, as they are often low cost and low technology. **Socio-cultural:** Some barriers to instruments like crop insurance, which some farmers in developing countries are not familiar with. (Goodwin and Smith 2013.)

Note: See note for Table 6.62.

6.4.2 Sensitivity of the integrated response options to climate change impacts

With continued increases in warming, there are risks to the efficacy of some of the response options due to future climate change impacts, such as increased climate variability and extreme events. While many of the response options can help increase capacity to deliver adaptation benefits (Section 6.3.2), beyond certain thresholds of climate impacts they may be less effective or increasingly risky options. This requires that some response options need to anticipate these climate impacts in their implementation. We outline some of these impacts below.

Agriculture response options: Increased food productivity as a response option is highly sensitive to climate change impacts. Chapter 5 (Section 5.2.3.1) notes that global mean yields of some crops (maize and soybean) decrease with warming, while others (rice and wheat) increase with warming, up to a threshold of 3°C. Similarly, improved cropland management response options that rely on crop diversification or improved varieties may face challenges in efficacy from production declines. Improved grazing land management may continue to be feasible as a response option in the future under climate change in northern regions, but will likely become more difficult in tropical regions and Australia as temperature rises will reduce the carrying capacity of lands (Nardone et al. 2010) (Section 5.2.3.2). Improved livestock management also faces numerous challenges, particularly related to stresses on animals from temperatures, water, and diseases; overall, livestock numbers are projected to decline 7.5–9.6% by 2050 (Rivera-Ferre et al. 2016; Boone et al. 2018) (Section 5.2.3.2). Pastoralists may also be less likely to implement improved measures due to other risks and vulnerabilities under climate change (Thornton et al. 2009).

The impact of climate change on agroforestry is more difficult to model than single crops in process-based crop models, as agroforestry systems are far more complex (Luedeling et al. 2014); thus, it is unknown how the efficacy of this response option might be impacted. Agricultural diversification has been promoted as an adaptive strategy to climate impacts, given that diversity is known to increase resiliency of agricultural and natural systems, such as in resistance to increased pests or diseases; it can also provide diversified income portfolios when some crops may become sensitive to climate events (Bradshaw et al. 2004; Lin 2011). Diversified farms are expected to increase in Africa by 2060 as specialised farms with single crops face challenges under climate change (Seo 2010). However, it is not known if these options and advantages of diversification have a temperature threshold beyond which they are less effective.

Reduced grassland conversion is not likely to be affected as a response option *per se* since it is directed at conserving natural grassland areas, but these areas may face increased pressures for conversion if farmers experience crop failures under climate change and need to expand the cultivated area holdings to make up for losses. Lobell et al. (2013) have estimated the impacts of investment decisions to adapt to the effects of climate change on crop yields to 2050 and find that cropland will expand over 23% more land area (over 3 Mkm^2), mostly in Latin America and Sub-Saharan Africa.

Integrated water management to improve water availability and reliability of water for agricultural production is likely to become more challenging in future scenarios of water declines, which are likely to be regionally uneven (Sections 2.6 and 6.4.4).

Forest response options: The availability of forest management as a response option can be impacted on by climate-induced changes, including increased diseases, pests and fires (Dale et al. 2001; Logan et al. 2003) (Section 4.5.1.2). These impacts will affect reforestation and afforestation response options as well. Locatelli et al. (2015a) note that climate change will influence seedling establishment, tree growth and mortality, and the presence of invasive species and/or pests; these can be buffered with modified silvicultural practices, including species selection (Pawson et al. 2013). Climate change can also alter the sink capacity for vegetation carbon sequestration, reducing the potential for reducing emissions from deforestation and forest degradation (REDD), reforestation and afforestation (Bonan 2008; Malhi et al. 2002).

Soil management: Climate change can alter the sink capacity for soil carbon sequestration, reducing the potential for increased soil organic carbon as an option. Projected climate change can reduce soil resilience to extreme weather, pests and biological invasion, environmental pollutants and other pressures, making reduced soil erosion and reduced soil compaction as response options harder to achieve (Smith et al. 2015). Climate change will likely increase demand for irrigation in dryland areas, which can increase risks of salinisation, diminishing the effectiveness of this response (Smith et al. 2015). Biochar additions to soil may be affected by future climatic changes, such as rising soil temperatures, but little is known, given that most research on the subject is from laboratory and not *in situ* field experiments. There are also wide estimates of the stability and residence times of biochar from this literature (Gurwick et al. 2013).

Other ecosystem management: Fire management is likely to become more challenging in a changing climate; some studies suggest an 50% increase in fire occurrence by the end of the century in circumboreal forests (Flannigan et al. 2009). Landslide risks are related to climate through total rainfall, rainfall intensity, air temperature and the general weather system (Gariano and Guzzetti 2016); thus reduced landslides and natural hazards as a response option will be made more difficult by increasing storms and seasonality of rainfall events projected for many areas of the world. Reduced pollution is likely less affected by climate change and can continue to be an option, despite increasing temperatures.

Conversely, some invasive species may thrive under climate change, such as moving to new areas or being less susceptible to control protocols (Hellmann et al. 2008). Conversion of coastal wetlands will be more difficult to halt if loss of productive land elsewhere encourages development on these lands, but coastal wetlands will likely adapt to increased CO_2 and higher sea levels through sediment accretion, which will also enhance their capacity to act as carbon sinks (Duarte et al. 2013). While subarctic peatlands are at risk due to warming, these are not the main peatlands that are at risk from agricultural conversion (Tarnocai 2006). Peatlands, such as those in the tropics, may be more vulnerable in hotter scenarios to water table alterations and fire risk (Gorham 1991). Biodiversity conservation, such as through protected areas or corridors, may be threatened by increased land expansion under agriculture in climate change scenarios, including the newly available land in northern climates that may become agriculturally suited (Gimona et al. 2012), lessening the effectiveness of this response option.

Carbon dioxide removal (CDR): The efficacy of enhanced weathering is not likely to be affected by future climate changes. On the other hand, climate change will affect the productivity of bioenergy crops (Cronin et al. 2018), influencing the mitigation potential of bioenergy and BECCS (Calvin et al. 2013; Kyle et al. 2014). There is uncertainty in the sign and magnitude of the effect of climate change on bioenergy crop yields. As a result, there is uncertainty in whether climate change will increase or decrease the potential of bioenergy and BECCS.

Demand management of value chains: For most response options in demand-side management, the tools are generally not made more difficult by future climate changes. For example, dietary change is not likely to be affected by climate change; in fact, the opposite is more likely, that diets will shift in response to climate change impacts as reflected in high prices for some staple grains and meats, the productivity of which may be reduced (Tigchelaar et al. 2018). However, there is some indication that fruit and vegetable production will also be reduced in future scenarios, making healthier diets potentially harder to achieve in some regions (Springmann et al. 2016). Reduced post-harvest losses and reduced food waste may become an even more important option if water or heat stresses under climate change reduce overall harvests. Material substitution does have risks related to the availability of products if there are declines in the growth of forest and other biomass in certain future scenarios over time, although some evidence indicates that biomass may increase in the short term with limited warming (Boisvenue and Running 2006).

Supply management of value chains: Sustainable sourcing relies on being able to produce consumer goods sustainably (palm oil, timber, cocoa, etc.), and these may be at risk; for example, areas suitable for oil palm production are estimated to decrease by 75% by 2100 (Paterson et al. 2017). Improved management of supply chains is likely to increase in importance as a tool to manage food security, given that climate change threatens to lead to more production shocks in the future (Baldos and Hertel 2015). For enhanced urban food systems, climate stresses like heat island effects or increased water scarcity in urban areas may reduce the viability of food production in certain urban systems (da Silva et al. 2012). Improved food processing and retailing and improved energy use in agriculture are not likely to be impacted on by climate change.

Risk management options: Most risk management response options are not affected by climate impacts *per se*, although the increased risks that people may face will increase the need for funding and support to deploy these options. For example, disaster risk management will likely increase in importance in helping people adapt to longer-term climate changes (Begum et al. 2014); it is also likely to cost more as increased impacts of climate change, such as intensification or frequency of storm events, may increase. Management of urban sprawl may also be challenged by increased migration driven by climate change, as people displaced by climate change may move to unregulated urban areas (Adamo 2010). Livelihood diversification can assist in adapting to climate changes and is not likely to be constrained as a response option, as climate-sensitive livelihoods may be replaced by others that are less so. Use of local seeds as an effective response option may depend on the specific types of seeds and crops used, as some may not be good choices under increased heat and water stress (Gross et al. 2017). Risk-sharing instruments are unlikely to be affected by climate change, with the exception of index and crop insurance, which may become unaffordable if too many climate shocks result in insurance claims, decreasing the ability of the industry to provide this tool (Mills 2005).

Cross-Chapter Box 8 | Ecosystem services and Nature's Contributions to People, and their relation to the land–climate system

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This Cross-Chapter Box describes the concepts of *ecosystem services* (ES) and *Nature's Contributions to People* (NCP), and their importance to land–climate interactions. ES have become a useful concept to describe the benefits that humans obtain from ecosystems and have strong relevance to sustainable land management (SLM) decisions and their outcomes, while NCP is a new approach championed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (explained below). It is timely that this SRCCL report includes attention to ES/NCP, as the previous Special Report on land-use, land-use change and forestry (LULUCF) did not make use of these concepts and focused mostly on carbon fluxes in land–climate interactions (IPCC 2000). The broader mandate of SRCCL is to address climate, but also land degradation, desertification and food security issues, all of which are closely linked to the provisioning of various ES/NCP, and the decision and outline for SRCCL explicitly request an examination of how desertification and degradation 'impacts on ecosystem services (e.g., water, soil and soil carbon and biodiversity that underpins them)'. Attention to ES/NCP is particularly important in discussing co-benefits, trade-offs and adverse side effects of potential climate change mitigation, land management, or food security response options, as many actions may have positive impacts on climate mitigation or food production, but may also come with a decline in ES provisioning, or adversely impact on biodiversity (Section 6.4.3). This box considers the importance of the ES/NCP concepts, how definitions have changed over time, continuing debates over operationalisation and use of these ideas. It concludes by looking at how ES/NCP are treated in various chapters in this report.

While the first uses of the term 'ecosystem services' appeared in the 1980s (Lele et al. 2013; Mooney and Ehrlich 1997), the roots of interest in ES extend back to the late 1960s and the extinction crisis, with concern that species decline might cause loss of valuable benefits to humankind (King 1966; Helliwell 1969; Westman 1977). While concern over extinction was explicitly linked to biodiversity loss, later ideas beyond biodiversity have animated interest in ES, including the multi-functional nature of ecosystems. A seminal paper by Costanza et al. (1997) attempted to put an economic value on the stocks of global ES and natural capital on which humanity relied. Attention to ES expanded rapidly after the Millennium Ecosystem Assessment (MA, 2005), and the linkages between ES and economic valuation of these functions were addressed by the Economics of Ecosystems and Biodiversity study (TEEB 2009). The ES approach has increasingly been used in global and national environmental assessments, including the UK National Ecosystem Assessment (Watson et al. 2011), and recent and ongoing regional and global assessments organised by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Díaz et al. 2015). IPBES has recently completed an assessment on land degradation and restoration that addresses a range of ES issues of relevance to the SRCCL report (IPBES 2018).

The MA defined ES as 'the benefits that ecosystems provide to people,' and identified four broad groupings of ES: *provisioning services* such as food, water, or timber; *regulating services* that have impacts on climate, diseases or water quality, among others; *cultural services* that provide recreational, aesthetic, and spiritual benefits; and *supporting services* such as soil formation, photosynthesis, and nutrient cycling (MA 2005). The MA emphasised that people are components of ecosystems engaged in dynamic interactions, and particularly assessed how changes in ES might impact human well-being, such as access to basic materials for living (shelter, clothing, energy); health (clean air and water); social relations (including community cohesion); security (freedom from natural disasters); and freedom of choice (the opportunity to achieve) (MA 2005). Upon publication of the MA, incorporation of ES into land-use change assessments increased dramatically, including studies on how to maximise provisioning of ES alongside human well-being (Carpenter et al. 2009); how intensive food production to feed growing populations required trading off a number of important ES (Foley et al. 2005); and how including ES in general circulation models indicated increasing vulnerability to ES change or loss in future climate scenarios (Schröter et al. 2005).

Starting in 2015, IPBES introduced a new related concept to ES, that of *Nature's Contributions to People* (NCP), which are defined as 'all the contributions, both positive and negative, of living nature (i.e., diversity of organisms, ecosystems and their associated ecological and evolutionary processes) to the quality of life of people' (Díaz et al. 2018). NCP are divided into regulating NCP, non-material NCP, and material NCP, a different approach than used by the MA (see Figure 1). However, IPBES has stressed that NCP are a particular *way to think* of ES, rather than a replacement for ES. The concept of NCP is proposed to be a broader umbrella to engage a wider range of scholarship – particularly from the social sciences and humanities – and a wider range of values, from intrinsic to instrumental to relational – particularly those held by indigenous peoples and local communities (Redford and Adams 2009; Schröter et al. 2014; Pascual et al. 2017; Díaz et al. 2018). The differences between the MA and IPBES approaches can be seen in Table 1.

While there are many similarities between ES and NCP, as seen above, the IPBES's decision to use the NCP concept has been controversial, with some people arguing that an additional term is superfluous; that it incorrectly associates ES with economic

6

Cross-Chapter Box 8 (continued)

Cross-Chapter Box 8, Table 1 | Comparison of MA and IPBES categories and types of ecosystem services (ES) and Nature's Contributions to People (NCP).

MA category	MA: ES	IPBES category	IPBES: NCP
Supporting services	Soil formation		
	Nutrient cycling		
	Primary production		
Regulating services		**Regulating contributions**	Habitat creation and maintenance
	Pollination		Pollination and dispersal of seeds and other propagules
	Air-quality regulation		Regulation of air quality
	Climate regulation		Regulation of climate
	Water regulation		Regulation of ocean acidification
	See above		Regulation of freshwater quantity, flow and timing
	Water purification and waste treatment		Regulation of freshwater and coastal water quality
	Erosion regulation		Formation, protection and decontamination of soils and sediments
	Natural hazard regulation		Regulation of hazards and extreme events
	Pest regulation and disease regulation		Regulation of organisms detrimental to humans
Provisioning services	Fresh water	**Material contributions**	Energy
	Food		Food and feed
	Fibre		Materials and assistance
	Medicinal and biochemical and genetic		Medicinal, biochemical and genetic resources
Cultural services	Aesthetic values	**Non-material contributions**	Learning and inspiration
	Recreation and ecotourism		Physical and psychological experiences
	Spiritual and religious values		Supporting identities
			Maintenance of options

Sources: MA 2005; Díaz et al. 2018.

valuation; and that the NCP concept is not useful for policy uptake (Braat 2018; Peterson et al. 2018). Others have argued that the MA's approach is outdated, does not explicitly address biodiversity, and confuses different concepts, like economic goods, ecosystem functions, and general benefits (Boyd and Banzhaf 2007). Moreover, for both ES and NCP approaches, it has been difficult to make complex ecological processes and functions amenable to assessments that can be used and compared across wider landscapes, different policy actors, and multiple stakeholders (de Groot et al. 2002; Naeem et al. 2015; Seppelt et al. 2011). There remain competing categorisation schemes for ES, as well as competing metrics on how most ES might be measured (Wallace 2007; Potschin and Haines-Young 2011; Danley and Widmark 2016; Nahlik et al. 2012). The implications of these discussions for this SRCCL report is that many areas of uncertainty remain with regard to much ES/NCP measurement and valuation, which will have ramifications for choosing response options and policies.

This report addresses ES/NCP in multiple ways. Individual chapters have used the term 'ES' in most cases, especially since the preponderance of existing literature uses the ES terminology. For example, Chapter 2 discusses CO_2 fluxes, nutrients and water budgets as important ES deriving from land–climate interactions. Chapters 3 and 4 discuss issues such as biomass production, soil erosion, biodiversity loss, and other ES affected by land-use change. Chapter 5 discusses both ES and NCP issues surrounding food system provisioning and trade-offs.

In Chapter 6, the concept of NCP is used. For example, Tables 6.70 to 6.72, possible response options to respond to climate change, to address land degradation or desertification, and to ensure food security, are cross-referenced against the 18 NCPs identified by Díaz et al. (2018) to see where there are co-benefits and adverse side effects. For instance, while BECCS may deliver on climate mitigation, it results in a number of adverse side effects that are significant with regard to water provisioning, food and feed availability, and loss of supporting identities if BECCS competes against local land uses of cultural importance. Chapter 7 has Section 7.2.2.2, explicitly covering risks due to loss of biodiversity and ES, and Table 7.1 which includes policy responses to various land–climate–society hazards, some of which are likely to enhance risk of loss of biodiversity and ES. A case study on the impact of renewable energy on biodiversity and ES is also included. Chapter 7 also notes that, because there is no Sustainable Development Goal covering freshwater biodiversity and aquatic ecosystems, this policy gap may have adverse consequences for the future of rivers and associated ES.

6.4.3 Impacts of integrated response options on Nature's Contributions to People (NCP) and the UN Sustainable Development Goals (SDGs)

In addition to evaluating the importance of our response options for climate mitigation, adaptation, land degradation, desertification and food security, it is also necessary to pay attention to other co-benefits and trade-offs that may be associated with these responses. How the different options impact progress toward the Sustainable Development Goals (SDGs) can be a useful shorthand for looking at the social impacts of these response options. Similarly, looking at how these response options increase or decrease the supply of ecosystem services/Nature's Contributions to People (NCP) (see Cross-Chapter Box 8 in Chapter 6) can be a useful shorthand for a more comprehensive environmental impact beyond climate and land. Such evaluations are important as response options may lead to unexpected trade-offs with social goals (or potential co-benefits) and impacts on important environmental indicators such as water or biodiversity. Similarly, there may be important synergies and co-benefits associated with some response options that may increase their cost-effectiveness or attractiveness. As we note in Section 6.4.4, many of these synergies are not automatic, and are dependent on well-implemented and coordinated activities in appropriate environmental contexts (Section 6.4.4.1), often requiring institutional and enabling conditions for success and participation of multiple stakeholders (Section 6.4.4.3).

In the following sections and tables, we evaluate each response option against 17 SDGs and 18 NCPs. Some of the SDG categories appear similar to each other, such as SDG 13 on 'climate action' and an NCP titled 'climate regulation'. However, SDG 13 includes targets for both mitigation and adaptation, so options were weighed by whether they were useful for one or both. On the other hand, the NCP 'regulation of climate' does not include an adaptation component, and refers specifically to 'positive or negative effects on emissions of GHGs and positive or negative effects on biophysical feedbacks from vegetation cover to atmosphere, such as those involving albedo, surface roughness, long-wave radiation, evapotranspiration (including moisture-recycling) and cloud formation or direct and indirect processes involving biogenic volatile organic compounds (BVOC), and regulation of aerosols and aerosol precursors by terrestrial plants and phytoplankton' (Díaz et al. 2018).

In all tables, colours represent the direction of impact: positive (blue) or negative (brown), and the scale of the impact (dark colours for large impact and/or strong evidence to light colours for small impact and/or less certain evidence). Supplementary tables show the values and references used to define the colour coding used in all tables. In cases where there is no evidence of an interaction, or at least no literature on such interactions, the cell is left blank. In cases where there are both positive and negative interactions and the literature is uncertain about the overall impact, a note appears in the box. In all cases, many of these interactions are contextual, or the literature only refers to certain co-benefits in specific regions or ecosystems, so readers are urged to consult the supplementary tables for the specific caveats that may apply.

6.4.3.1 Impacts of integrated response options on NCP

Tables 6.70–6.72 summarise the impacts of the response options on NCP supply. Examples of synergies between response options and NCP include positive impacts on habitat maintenance (NCP 1) from activities like invasive species management and agricultural diversification. For the evaluation process, we considered that NCP are about ecosystems, therefore options which may have overall positive effects, but which are *not* ecosystem-based are not included; for example, improved food transport and distribution could reduce ground-level ozone and thus improve air quality, but this is not an ecosystem-based NCP. Similarly, energy-efficiency measures would increase energy availability, but the 'energy' NCP refers specifically to biomass-based fuel provisioning. This necessarily means that the land management options have more direct NCP effects than the value chain or governance options, which are less ecosystem focused.

In evaluating NCP, we have also tried to avoid 'indirect' effects – that is, a response option might increase household income which could then be invested in habitat-saving actions, or dietary change would lead to conservation of natural areas, which would then lead to increased water quality. Similarly, material substitution would increase wood demand, which in turn might lead to deforestation, which might have water regulation effects. These can all be considered *indirect* impacts on NCP, which were not evaluated.[8] Instead, the assessment focuses as much as possible on *direct* effects only: for example, local seeds policies preserve local landraces, which *directly* contribute to 'maintenance of genetic options' for the future. Therefore, this NCP table is a conservative estimation of NCP effects; there are likely many more secondary effects, but they are too difficult to assess, or the literature is not yet complete or conclusive.

Further, many NCPs trade-off with one another (Rodríguez et al. 2006), so supply of one might lead to less availability of another – for example, use of ecosystems to produce bioenergy will likely lead to decreases in water availability if mono-cropped high-intensity plantations are used (Gasparatos et al. 2011).

Overall, several response options stand out as having co-benefits across 10 or more NCP with no adverse impacts, including: improved cropland management, agroforestry, forest management and forest restoration, increased soil organic content, fire management, restoration and avoided conversion of coastal wetlands, and use of local seeds. Other response options may have strengths in some NCP but require trade-offs with others. For example, reforestation and afforestation bring many positive benefits for climate and water quality but may trade-off with food production (Table 6.70). Several response options, including increased food productivity, bioenergy and BECCS, and some risk-sharing instruments, like crop insurance, have significant negative consequences across multiple NCPs.

8 The exception is NCP 6, regulation of ocean acidification, which is by itself an indirect impact. Any option that sequesters CO_2 would lower the atmospheric CO_2 concentration, which then indirectly increases the seawater pH. Therefore, any action that directly increases the amount of sequestered carbon is noted in this column, but not any action that avoids land-use change and, therefore, indirectly avoids CO_2 emissions.

Table 6.70 | Impacts on Nature's Contributions to People (NCP) of integrated response options based on land management.

Integrated response options based on land management	Habitat creation and maintenance	Pollination and dispersal of seeds and other propagules	Regulation of air quality	Regulation of climate	Regulation of ocean acidification	Regulation of freshwater quantity, flow and timing	Regulation of freshwater and coastal water quality	Formation, protection and decontamination of soils and sediments	Regulation of hazards and extreme events	Regulation of organisms detrimental to humans	Energy	Food and feed	Materials and assistance	Medicinal, biochemical and genetic resources	Learning and inspiration	Physical and psychological experiences	Supporting identities	Maintenance of options
Increased food productivity																		
Improved cropland management																		
Improved grazing land management																		
Improved livestock management																		
Agroforestry																		
Agricultural diversification																		
Avoidance of conversion of grassland to cropland																		
Integrated water management													+ or –					
Forest management and forest restoration									+ or –				+ or –					
Reduced deforestation and forest degradation																		
Reforestation									+ or –									
Afforestation								+ or –	+ or –									
Increased soil organic carbon content																		
Reduced soil erosion																		
Reduced soil salinisation																		
Reduced soil compaction																		
Biochar addition to soil																		
Fire management																		
Reduced landslides and natural hazards																		
Reduced pollution including acidification																		
Management of invasive species/encroachment																		
Restoration and avoided conversion of coastal wetlands												+ or –						
Restoration and avoided conversion of peatlands																		
Biodiversity conservation												+ or –						
Enhanced weathering of minerals																		
Bioenergy and BECCS[9]																		

Large positive impacts, strong evidence
Medium positive impacts, some evidence
Small positive impacts or low evidence
Low negative impacts or low evidence
Medium negative impacts, medium evidence
Large negative impacts, high evidence

9 Note that this refers to large areas of bioenergy crops capable of producing large mitigation benefits (>3 GtCO_2 yr^{-1}). The effect of bioenergy and BECCS on NCPs is scale and context dependent (see Cross-Chapter Box 7 in Chapter 6 and Section 6.3).

Table 6.71 | Impacts on NCP of integrated response options based on value chain management.

Integrated response options based on value chain management	Habitat creation and maintenance	Pollination and dispersal of seeds and other propagules	Regulation of air quality	Regulation of climate	Regulation of ocean acidification	Regulation of freshwater quantity, flow and timing	Regulation of freshwater and coastal water quality	Formation, protection and decontamination of soils and sediments	Regulation of hazards and extreme events	Regulation of organisms detrimental to humans	Energy	Food and feed	Materials and assistance	Medicinal, biochemical and genetic resources	Learning and inspiration	Physical and psychological experiences	Supporting identities	Maintenance of options
Dietary change																		
Reduced post-harvest losses																		
Reduced food waste (consumer or retailer)																		
Material substitution																		
Sustainable sourcing																		
Management of supply chains																		
Enhanced urban food systems																		
Improved food processing and retail																		
Improved energy use in food systems																		

Large positive impacts, strong evidence
Medium positive impacts, some evidence
Small positive impacts or low evidence
Low negative impacts or low evidence

Table 6.72 | Impacts on NCP of integrated response options based on risk management.

Integrated response options based on risk management	Habitat creation and maintenance	Pollination and dispersal of seeds and other propagules	Regulation of air quality	Regulation of climate	Regulation of ocean acidification	Regulation of freshwater quantity, flow and timing	Regulation of freshwater and coastal water quality	Formation, protection and decontamination of soils and sediments	Regulation of hazards and extreme events	Regulation of organisms detrimental to humans	Energy	Food and feed	Materials and assistance	Medicinal, biochemical and genetic resources	Learning and inspiration	Physical and psychological experiences	Supporting identities	Maintenance of options
Management of urban sprawl																		
Livelihood diversification																		
Use of local seeds																		
Disaster risk management																		
Risk-sharing instruments																		

Large positive impacts, strong evidence
Medium positive impacts, some evidence
Small positive impacts or low evidence
Low negative impacts or low evidence
Medium negative impacts, medium evidence

6.4.3.2 Impacts of integrated response options on the UN SDGs

Tables 6.73–6.75 summarise the impact of the integrated response options on the UN SDGs. Some of the synergies between response options and SDGs in the literature include positive poverty eradication impacts (SDG 1) from activities like improved water management or improved management of supply chains, or positive gender impacts (SDG 5) from livelihood diversification or use of local seeds. Because many land management options only produce indirect or unclear effects on SDGs, we did not include these where there was no literature. Therefore, the value chain and governance options appear to offer more direct benefits for SDG.

However, it is noted that some SDG are internally difficult to assess because they contain many targets, not all of which could be evaluated (e.g., SDG 17 is about partnerships, but has targets ranging from foreign aid to debt restructuring, technology transfer to trade openness). Additionally, it is noted that some SDG contradict one another – for example, SDG 9 to increase industrialisation and infrastructure and SDG 15 to improve life on land. More industrialisation is likely to lead to increased resource demands with negative effects on habitats. Therefore, a positive association on one SDG measure might be directly correlated with a negative measure on another, and the table needs to be read with caution for that reason. The specific caveats on each of these interactions can be found in the supplementary material tables in the Chapter 6 Appendix.

Overall, several response options have co-benefits across 10 or more SDGs with no adverse side effects on any SDG: increased food production, improved grazing land management, agroforestry, integrated water management, reduced post-harvest losses, sustainable sourcing, livelihood diversification and disaster risk management. Other response options may have strengths in some SDGs but require trade-offs with others. For example, use of local seeds brings many positive benefits for poverty and hunger reduction, but may reduce international trade (SDG 17). Other response options like enhanced urban food systems, management of urban sprawl, or management of supply chains are generally positive for many SDGs but may trade-off with one, like clean water (SDG 6) or decent work (SDG 8), as they may increase water use or slow economic growth. Several response options, including avoidance of grassland conversion, reduced deforestation and forest degradation, reforestation and afforestation, biochar, restoration and avoided conversion of peatlands and coastlands, have trade-offs across multiple SDGs, primarily as they prioritise land health over food production and poverty eradication. Several response options such as bioenergy and BECCS and some risk-sharing instruments, such as crop insurance, trade-off over multiple SDG with potentially significant adverse consequences.

Overall, across categories of SDG and NCPs; 17 of 40 options deliver co-benefits or no adverse side effects for the full range of NCPs and SDGs. This includes most agriculture- and soil-based land management options, many ecosystem-based land management options, forest management, reduced post-harvest losses, sustainable sourcing, improved energy use in food systems, and livelihood diversification. Only three options (afforestation, bioenergy and BECCS and some types of risk-sharing instruments, such as crop insurance) have potentially adverse side effects for five or more NCPs or SDGs.

Table 6.73 | Impacts of integrated response options based on land management on the UN SDGs.

Integrated response options based on land management	GOAL 1: No poverty	GOAL 2: Zero hunger	GOAL 3: Good health and well-being	GOAL 4: Quality education	GOAL 5: Gender equality	GOAL 6: Clean water and sanitation	GOAL 7: Affordable and clean energy	GOAL 8: Decent work and economic growth	GOAL 9: Industry, innovation and infrastructure	GOAL 10: Reduced inequality	GOAL 11: Sustainable cities and communities	GOAL 12: Responsible consumption and production	GOAL 13: Climate action	GOAL 14: Life below water	GOAL 15: Life on land	GOAL 16: Peace, justice and strong institutions	GOAL 17: Partnerships to achieve the goals
Increased food productivity																	
Improved cropland management																	
Improved grazing land management																	
Improved livestock management																	
Agroforestry																	
Agricultural diversification										+ or –							
Avoidance of conversion of grassland to cropland																	
Integrated water management																	
Forest management and forest restoration																	
Reduced deforestation and forest degradation	+ or –																
Reforestation	+ or –																
Afforestation																	
Increased soil organic carbon content																	
Reduced soil erosion																	
Reduced soil salinisation																	
Reduced soil compaction																	
Biochar addition to soil																	
Fire management																	
Reduced landslides and natural hazards																	
Reduced pollution, including acidification																	
Management of invasive species/encroachment																	
Restoration and avoided conversion of coastal wetlands	+ or –	+ or –															
Restoration and avoided conversion of peatlands																	
Biodiversity conservation																	
Enhanced weathering of minerals																	
Bioenergy and BECCS[10]	+ or –		+ or –														

Large positive impacts, strong evidence
Medium positive impacts, some evidence
Small positive impacts or low evidence
Low negative impacts or low evidence
Medium negative impacts, medium evidence
Large negative impacts, high evidence

10 Note that this refers to large areas of bioenergy crops capable of producing large mitigation benefits (>3 $GtCO_2\ yr^{-1}$). The effect of bioenergy and BECCS on SDGs is scale and context dependent (see Cross-Chapter Box 7 in Chapter 6 and Section 6.3).

Table 6.74 | Impacts of integrated response options based on value chain interventions on the UN SDGs.

Integrated response options based on value chain management	GOAL 1: No poverty	GOAL 2: Zero hunger	GOAL 3: Good health and well-being	GOAL 4: Quality education	GOAL 5: Gender equality	GOAL 6: Clean water and sanitation	GOAL 7: Affordable and clean energy	GOAL 8: Decent work and economic growth	GOAL 9: Industry, innovation and infrastructure	GOAL 10: Reduced inequality	GOAL 11: Sustainable cities and communities	GOAL 12: Responsible consumption and production	GOAL 13: Climate action	GOAL 14: Life below water	GOAL 15: Life on land	GOAL 16: Peace, justice and strong institutions	GOAL 17: Partnerships to achieve the goals
Dietary change																	
Reduced post-harvest losses																	
Reduced food waste (consumer or retailer)																	
Material substitution																	
Sustainable sourcing																	
Management of supply chains																	
Enhanced urban food systems																	
Improved food processing and retail																	
Improved energy use in food systems																	

Large positive impacts, strong evidence
Medium positive impacts, some evidence
Small positive impacts or low evidence
Low negative impacts or low evidence
Medium negative impacts, medium evidence

Table 6.75 | Impacts of integrated response options based on risk management on the UN SDGs.

Integrated response options based on risk management	GOAL 1: No poverty	GOAL 2: Zero hunger	GOAL 3: Good health and well-being	GOAL 4: Quality education	GOAL 5: Gender equality	GOAL 6: Clean water and sanitation	GOAL 7: Affordable and clean energy	GOAL 8: Decent work and economic growth	GOAL 9: Industry, innovation and infrastructure	GOAL 10: Reduced inequality	GOAL 11: Sustainable cities and communities	GOAL 12: Responsible consumption and production	GOAL 13: Climate action	GOAL 14: Life below water	GOAL 15: Life on land	GOAL 16: Peace, justice and strong institutions	GOAL 17: Partnerships to achieve the goals
Management of urban sprawl																	
Livelihood diversification																	
Use of local seeds																	
Disaster risk management																	
Risk-sharing instruments												+ or –					

Large positive impacts, strong evidence
Medium positive impacts, some evidence
Small positive impacts or low evidence
Low negative impacts or low evidence

6.4.4 Opportunities for implementing integrated response options

6.4.4.1 Where can the response options be applied?

As shown in Section 6.1.3, a large part of the land area is exposed to overlapping land challenges, especially in villages, croplands and rangelands. The deployment of land management responses may vary with local exposure to land challenges. For instance, with croplands exposed to a combination of land degradation, food insecurity and climate change adaptation challenges, maximising the co-benefits of land management responses would require selecting responses having only co-benefits for these three overlapping challenges, as well as for climate change mitigation, which is a global challenge. Based on these criteria, Figure 6.6 shows the potential deployment area of land management responses across land-use types (or anthromes).

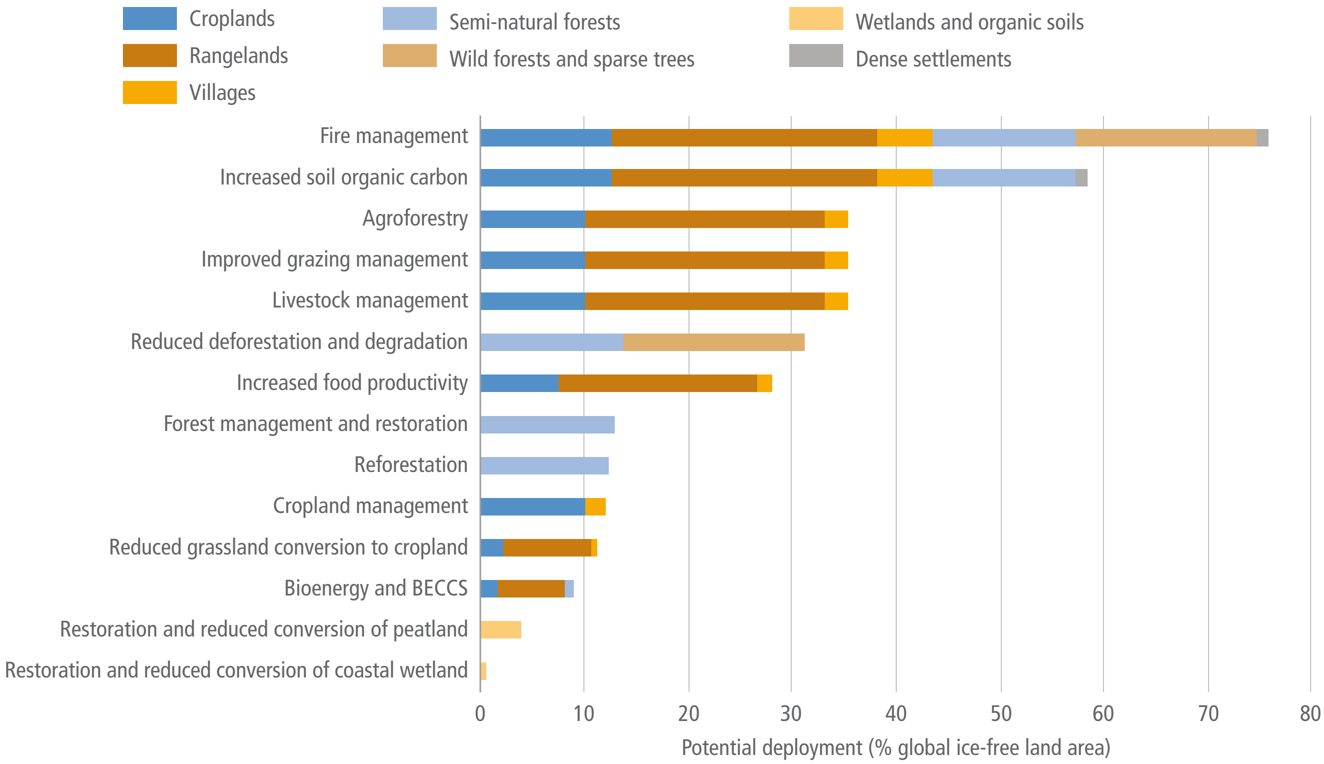

Figure 6.6 | Potential deployment area of land management responses (see Table 6.1) across land-use types (or anthromes, see Section 6.3), when selecting responses having only co-benefits for local challenges and for climate change mitigation and no large adverse side effects on global food security. See Figure 6.2 for the criteria used to map challenges considered (desertification, land degradation, climate change adaptation, chronic undernourishment, biodiversity, groundwater stress and water quality). No response option was identified for barren lands.

Land management responses having co-benefits across the range of challenges, including climate change mitigation, could be deployed between one land-use type (coastal wetlands, peatlands, forest management and restoration, reforestation) and five (increased soil organic carbon) or six (fire management) land-use types (Figure 6.6). Fire management and increased soil organic carbon have a large potential since they could be deployed with mostly co-benefits and few adverse effects over 76% and 58% of the ice-free land area. In contrast, other responses have a limited area-based potential due to biophysical constraints (e.g., limited extent of organic soils and of coastal wetlands for conservation and restoration responses), or due to the occurrence of adverse effects. Despite strong co-benefits for climate change mitigation, the deployment of bioenergy and BECCS would have co-benefits on only 9% of the ice-free land area (Figure 6.6), given adverse effects of this response option for food security, land degradation, climate change adaptation and desertification (Tables 6.62–6.69).

Without including the global climate change mitigation challenge, there are up to five overlapping challenges on lands that are not barren (Figure 6.7A, calculated from the overlay of individual challenges shown in Figure 6.2) and up to nine land management response options having only co-benefits for these challenges and for climate change mitigation (Figure 6.7B). Across countries, the mean number of land management response options with mostly co-benefits declines (p<0.001, Spearman rank order correlation) with the mean number of land challenges. Hence, the higher the number of land challenges per country, the fewer the land management response options having only co-benefits for the challenges encountered.

Enabling conditions (see Section 6.1.2.2) for the implementation of land management responses partly depend on human development (economics, health and education) as estimated by a country scale composite index, the Human Development Index (HDI) (UNDP 2018) (Figure 6.7C). Across countries, HDI is negatively correlated (p<0.001, Spearman rank order correlation) with the mean number of land challenges. Therefore, on a global average, the higher the number of local challenges faced, the fewer the land management responses having only co-benefits, and the lower the human development (Figure 6.7) that could favour the implementation of these responses.

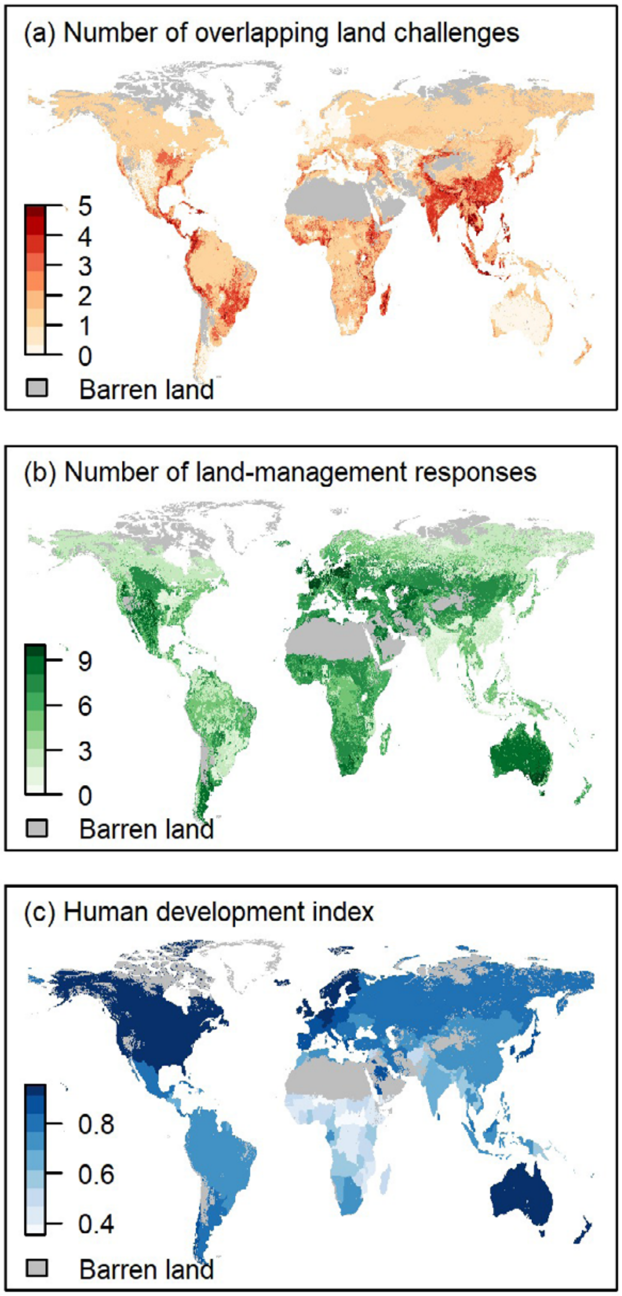

Figure 6.7 | Global distributions of: **(a)** number of overlapping land challenges (desertification, land degradation, climate change adaptation, chronic undernourishment, biodiversity, groundwater stress and water quality (Figure 6.2); **(b)** number of land management responses providing medium-to-large co-benefits and no adverse side effects (see Figure 6.6) across challenges; **(c)** Human Development Index (HDI) by country. The HDI (UNDP 2018) is a country-based composite statistical index measuring average achievement in three basic dimensions of human development: a long and healthy life (estimated from life expectancy at birth), knowledge (estimated from years of schooling), and a decent standard of living (estimated from gross national income per capita).

6.4.4.2 Interlinkages and response options in future scenarios

This section assesses more than 80 articles quantifying the effect of various response options in the future, covering a variety of response options and land-based challenges. These studies cover spatial scales ranging from global (Popp et al. 2017; Fujimori et al. 2019) to regional (Calvin et al. 2016a; Frank et al. 2015) to country level (Gao and Bryan 2017; Pedercini et al. 2018). This section focuses on models that can quantify interlinkages between response options, including agricultural economic models, land system models, and Integrated Assessment Models (IAMs). The IAM and non-IAM literature, however, is also categorised separately to elucidate what is and is not included in global mitigation scenarios, like those included in the SR15. Results from bottom-up studies and models (e.g., Griscom et al. 2017) are assessed in Sections 6.2–6.3.

Response options in future scenarios

More than half of the 40 land-based response options discussed in this chapter are represented in global IAMs models used to develop and analyse future scenarios, either implicitly or explicitly (Table 6.76). For example, all IAMs include improved cropland management, either explicitly through technologies that improve nitrogen use efficiency (Humpenöder et al. 2018) or implicitly through marginal abatement cost curves that link reductions in nitrous oxide emissions from crop production to carbon prices (most other models).

However, the literature discussing the effect of these response options on land-based challenges is more limited (Table 6.76). There are 57 studies (43 IAM studies) that articulate the effect of response options on mitigation, with most including bioenergy and BECCS or a combination of reduced deforestation, reforestation, and afforestation; 37 studies (21 IAM studies) discuss the implications of response options on food security, usually using food price as a metric. While a small number of non-IAM studies examine the effects of response options on desertification (three studies) and land degradation (five studies), no IAM studies were identified. However, some studies quantify these challenges indirectly using IAMs, either via climate outputs from the representative concentration pathways (RCPs) (Huang et al. 2016) or by linking IAMs to other land and ecosystem models (Ten Brink et al. 2018; UNCCD 2017).

For many of the scenarios in the literature, land-based response options are included as part of a suite of mitigation options (Popp et al. 2017; Van Vuuren et al. 2015). As a result, it is difficult to isolate the effect of an individual option on land-related challenges. A few studies focus on specific response options (Calvin et al. 2014; Popp et al. 2014; Kreidenweis et al. 2016; Humpenöder et al. 2018), quantifying the effect of including an individual option on a variety of sustainability targets.

Table 6.76 | Number of IAM and non-IAM studies including specific response options (rows) and quantifying particular land challenges (columns). The third column shows how many IAM models include the individual response option. The remaining columns show challenges related to climate change (C), mitigation (M), adaptation (A), desertification (D), land degradation (L), food security (F), and biodiversity/ecosystem services/sustainable development (B). Additionally, counts of total (left value) and IAM-only (right value) studies are included. Some IAMs include agricultural economic models, which can also be run separately; these models are not counted as IAM literature when used on their own. Studies using a combination of IAMs and non-IAMs are included in the total only. A complete list of studies is included in the Appendix.

Category	Response option	IAMs[a]	Studies [Total/IAM]						
			C	M	A	D	L[b]	F[c]	B
Land management	Increased food productivity		1/1	18/14	5/1	2/0	3/0	18/9	12/6
	Improved cropland management		0/0	15/11	7/2	0/0	0/0	13/6	7/4
	Improved grazing land management		0/0	1/0	1/0	0/0	0/0	1/0	0/0
	Improved livestock management		0/0	10/6	1/0	2/0	2/0	7/3	5/2
	Agroforestry		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Agricultural diversification		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Reduced grassland conversion to cropland		0/0	2/2	0/0	0/0	0/0	1/1	1/1
	Integrated water management		1/0	17/12	5/2	0/0	2/0	13/7	20/13
	Forest management		0/0	2/0	0/0	1/0	1/0	2/0	2/0
	Reduced deforestation and forest degradation		2/2	24/20	1/0	1/0	1/0	14/9	14/8
	Reforestation and forest restoration		3/3	19/18	1/1	1/0	2/0	9/8	9/6
	Afforestation		3/3	24/21	2/1	0/0	0/0	10/9	8/7
	Increased soil organic carbon content		0/0	3/1	0/0	0/0	0/0	1/1	0/0
	Reduced soil erosion		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Reduced soil salinisation		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Reduced soil compaction		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Biochar addition to soil		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Fire management		0/0	1/1	0/0	0/0	0/0	0/0	0/0
	Reduced landslides and natural hazards		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Reduced pollution, including acidification		2/2	18/16	2/1	0/0	0/0	10/7	6/6
	Management of invasive species/encroachment		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Restoration and reduced conversion of coastal wetlands		0/0	0/0	0/0	1/0	1/0	0/0	1/0
	Restoration and reduced conversion of peatlands		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Biodiversity conservation		1/0	7/3	0/0	1/0	3/0	4/2	8/1
	Enhanced weathering of minerals		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Bioenergy and BECCS		5/4	50/40	7/4	0/0	2/0	25/18	21/13
Value chain management	Dietary change		0/0	15/12	1/0	2/0	2/0	13/9	10/7
	Reduced post-harvest losses		0/0	5/4	0/0	0/0	0/0	2/2	2/1
	Reduced food waste (consumer or retailer)		0/0	6/4	0/0	0/0	0/0	4/2	3/1
	Material substitution		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Sustainable sourcing		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Management of supply chains		1/1	11/9	8/1	2/0	3/0	17/9	7/3
	Enhanced urban food systems		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Improved food processing and retailing		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Improved energy use in food systems		0/0	0/0	0/0	0/0	0/0	0/0	0/0
Risk management	Management of urban sprawl		0/0	0/0	0/0	1/0	1/0	0/0	1/0
	Livelihood diversification		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Use of local seeds		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Disaster risk management		0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Risk sharing instruments		0/0	0/0	0/0	0/0	0/0	0/0	0/0

IAMs: How many models include the individual response option

All models · Less than half · More than half · No models

Columns C, M, A, D, L, F and B: Number of total studies

0 · 6–10 · 16+ · 1–5 · 11–15

[a] Only IAMs that are used in the papers assessed are included in this column.
[b] There are many indicators for land degradation (Chapter 4). In this table, studies are categorised as quantifying land degradation if they explicitly discuss land degradation.
[c] Studies are categorised is quantifying food security if they report food prices or the population at risk of hunger.

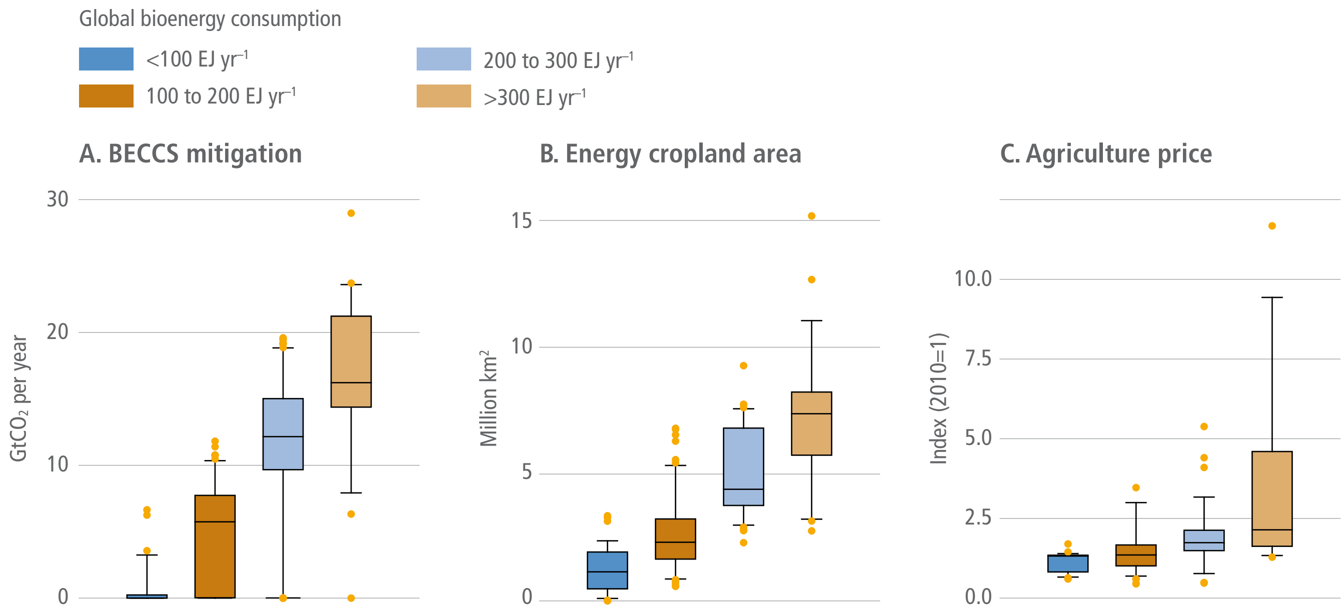

Figure 6.8 | Correlation between bioenergy use and other indicators. Panel A shows global CO_2 sequestration by BECCS in 2100. **Panel B** shows global energy cropland area in 2100. **Panel C** shows agricultural prices in 2100 indexed to 2010. Data are based on the amount of bioenergy used globally in 2100. All scenario data that include bioenergy consumption and the variable of interest are included in the figure; the resulting number of scenarios varies per panel, with 352 in panel A, 262 in panel B, and 172 in panel C. The boxes represent the interquartile range (i.e., the middle 50% of all scenarios). The line in the middle of the box represents the median, and the 'whiskers' represent the 5 to 95% range of scenarios. Data is from an update of the Integrated Assessment Modelling Consortium (IAMC) Scenario Explorer developed for the SR15 (Huppmann et al. 2018; Rogelj et al. 2018b).

Interactions and interlinkages between response options

The effect of response options on desertification, land degradation, food security, biodiversity, and other SDGs depends strongly on which options are included, and the extent to which they are deployed. For example, Sections 2.6 and 6.3.6, and Cross-Chapter Box 7 note that bioenergy and BECCS has a large mitigation potential, but could potentially have adverse side effects for land degradation, food security, and other SDGs. Global modelling studies demonstrate that these effects are dependent on scale. Increased use of bioenergy can result in increased mitigation (Figure 6.8, panel A) and reduced climate change, but can also lead to increased energy cropland expansion (Figure 6.8, panel B), and increased competition for land, resulting in increased food prices (Figure 6.8, panel C). However, the exact relationship between bioenergy deployment and each sustainability target depends on a number of other factors, including the feedstock used, the underlying socio-economic scenario, assumptions about technology and resource base, the inclusion of other response options, and the specific model used (Calvin et al. 2014; Clarke et al. 2014; Popp et al. 2014, 2017; Kriegler et al. 2014).

The previous sections have examined the effects of individual land-response options on multiple challenges. A number of studies using global modelling and analyses have examined interlinkages and interaction effects among land response options by incrementally adding or isolating the effects of individual options. Most of these studies focus on interactions with bioenergy and BECCS (Table 6.77). Adding response options that require land (e.g., reforestation, afforestation, reduced deforestation, avoided grassland conversion, or biodiversity conservation) results in increased food prices (Calvin et al. 2014; Humpenöder et al. 2014; Obersteiner et al. 2016; Reilly et al. 2012) and potentially increased temperature through biophysical climate effects (Jones et al. 2013). However, this combination can result in reduced water consumption (Hejazi et al. 2014b), reduced cropland expansion (Calvin et al. 2014; Humpenöder et al. 2018), increased forest cover (Calvin et al. 2014; Humpenöder et al. 2018; Wise et al. 2009) and reduced biodiversity loss (Pereira et al. 2010), compared to scenarios with bioenergy and BECCS alone. While these options increase total mitigation, they reduce mitigation from bioenergy and BECCS as they compete for the same land (Wu et al. 2019; Baker et al. 2019; Calvin et al. 2014; Humpenöder et al. 2014).

The inclusion of land-sparing options (e.g., dietary change, increased food productivity, reduced food waste, management of supply chains) in addition to bioenergy and BECCS results in reduced food prices, reduced agricultural land expansion, reduced deforestation, reduced mitigation costs, reduced water use, and reduced biodiversity loss (Bertram et al. 2018; Wu et al. 2019; Obersteiner et al. 2016; Stehfest et al. 2009; Van Vuuren et al. 2018). These options can increase bioenergy potential, resulting in increased mitigation than from bioenergy and BECCS alone (Wu et al. 2019; Stehfest et al. 2009; Favero and Massetti 2014).

Other combinations of land response options create synergies, alleviating land pressures. The inclusion of increased food productivity and dietary change can increase mitigation, reduce cropland use, reduce water consumption, reduce fertiliser application, and reduce biodiversity loss (Springmann et al. 2018; Obersteiner et al. 2016). Similarly, improved livestock management, combined with increased food productivity, can reduce agricultural land expansion (Weindl et al. 2017). Reducing disturbances (e.g., fire management) in combination with afforestation can increase the terrestrial carbon sink, resulting in increased mitigation potential and reduced mitigation cost (Le Page et al. 2013).

Studies including multiple land response options often find that the combined mitigation potential is not equal to the sum of individual mitigation potential as these options often share the same land. For example, including both afforestation and bioenergy and BECCS results in a cumulative reduction in GHG emissions of 1200 $GtCO_2$ between 2005 and 2100, which is much lower than the sum of the contributions of bioenergy (800 $GtCO_2$) and afforestation (900 $GtCO_2$) individually (Humpenöder et al. 2014). More specifically, Baker et al. (2019) find that woody bioenergy and afforestation are complementary in the near term, but become substitutes in the long term, as they begin to compete for the same land. Similarly, the combined effect of increased food productivity, dietary change and reduced waste on GHG emissions is less than the sum of the individual effects (Springmann et al. 2018).

Table 6.77 | Interlinkages between bioenergy and BECCS and other response options. Table indicates the combined effects of multiple land-response options on climate change (C), mitigation (M), adaptation (A), desertification (D), land degradation (L), food security (F), and biodiversity/ecosystem services/sustainable development (O). Each cell indicates the implications of adding the option specified in the row in addition to bioenergy and BECCS. Blue colours indicate positive interactions (e.g., including the option in the second column increases mitigation, reduces cropland area, or reduces food prices relative to bioenergy and BECCS alone). Yellow indicates negative interactions; grey indicates mixed interactions (some positive, some negative). Note that only response option combinations found in the assessed literature are included in the interest of space.

	C[a]	M[b]	A	D	L[c]	F	O[d]	Context and sources
Increased food productivity								Humpenöder et al. 2018; Obersteiner et al. 2016
Increased food productivity; improved livestock management								Van Vuuren et al. 2018
Improved cropland management								Humpenöder et al. 2018
Integrated water management								O: Reduces water use, but increases fertiliser use. (Humpenöder et al. 2018)
Reduced deforestation								Calvin et al. 2014; Humpenöder et al. 2018
Reduced deforestation, avoided grassland conversion								O: Reduces biodiversity loss and fertiliser, but increases water use. (Calvin et al. 2014; Obersteiner et al. 2016)
Reforestation								Reilly et al. 2012
Reforestation, afforestation, avoided grassland conversion								Calvin et al. 2014; Hejazi et al. 2014a; Jones et al. 2013
Afforestation								Humpenöder et al. 2014
Biodiversity conservation								M: Reduces emissions but also reduces bioenergy potential. O: Reduces biodiversity loss but increases water use. (Obersteiner et al. 2016; Wu et al. 2019)
Reduced pollution								Van Vuuren et al. 2018
Dietary change								Bertram et al. 2018; Stehfest et al. 2009; Wu et al. 2019
Reduced food waste; dietary change								Van Vuuren et al. 2018
Management of supply chains								Favero and Massetti 2014
Management of supply chains; increased productivity								Wu et al. 2019
Reduced deforestation; improved cropland management; improved food productivity; integrated water management								Humpenöder et al. 2018
Reduced deforestation; management of supply chains; integrated water management; improved cropland management; increased food productivity								Bertram et al. 2018
Reduced deforestation; management of supply chains; integrated water management; improved cropland management; increased food productivity; dietary change								Bertram et al. 2018

Positive interactions Negative interactions Mixed interactions

[a] Includes changes in biophysical effects on climate (e.g., albedo).
[b] Either through reduced emissions, increased mitigation, reduced mitigation cost, or increased bioenergy potential. For increased mitigation, a positive indicator in this column only indicates that total mitigation increases and not that the total is greater than the sum of the individual options.
[c] Use changes in cropland or forest as an indicator (reduced cropland expansion or reduced deforestation are considered positive).
[d] Includes changes in water use or scarcity, fertiliser use, or biodiversity.

Land-related response options can also interact with response options in other sectors. For example, limiting deployment of a mitigation response option will either result in increased climate change or additional mitigation in other sectors. A number of studies have examined limiting bioenergy and BECCS. Some such studies show increased emissions (Reilly et al. 2012). Other studies meet the same climate goal, but reduce emissions elsewhere *via* reduced energy demand (Grubler et al. 2018; Van Vuuren et al. 2018), increased fossil carbon capture and storage (CCS), nuclear energy, energy efficiency and/or renewable energy (Van Vuuren et al. 2018; Rose et al. 2014; Calvin et al. 2014; Van Vuuren et al. 2017b), dietary change (Van Vuuren et al. 2018), reduced non-CO_2 emissions (Van Vuuren et al. 2018), or lower population (Van Vuuren et al. 2018). The co-benefits and adverse side effects of non-land mitigation options are discussed in SR15, Chapter 5. Limitations on bioenergy and BECCS can result in increases in the cost of mitigation (Kriegler et al. 2014; Edmonds et al. 2013). Studies have also examined limiting CDR, including reforestation, afforestation, and bioenergy and BECCS (Kriegler et al. 2018a,b). These studies find that limiting CDR can increase mitigation costs, increase food prices, and even preclude limiting warming to less than 1.5°C above pre-industrial levels (Kriegler et al. 2018a,b; Muratori et al. 2016).

In some cases, the land challenges themselves may interact with land-response options. For example, climate change could affect the production of bioenergy and BECCS. A few studies examine these effects, quantifying differences in bioenergy production (Calvin et al. 2013; Kyle et al. 2014) or carbon price (Calvin et al. 2013) as a result of climate change. Kyle et al. (2014) find increase in bioenergy production due to increases in bioenergy yields, while Calvin et al. (2013) find declines in bioenergy production and increases in carbon price due to the negative effects of climate on crop yield.

Gaps in the literature

Not all of the response options discussed in this chapter are included in the assessed literature, and many response options are excluded from the IAM models. The included options (e.g., bioenergy and BECCS; reforestation) are some of the largest in terms of mitigation potential (see Section 6.3). However, some of the options excluded also have large mitigation potential. For example, biochar, agroforestry, restoration/avoided conversion of coastal wetlands, and restoration/avoided conversion of peatland all have mitigation potential of about 1 $GtCO_2$ yr^{-1} (Griscom et al. 2017). Additionally, quantifications of and response options targeting land degradation and desertification are largely excluded from the modelled studies, with a few notable exceptions (Wolff et al. 2018; Gao and Bryan 2017; Ten Brink et al. 2018; UNCCD 2017). Finally, while a large number of papers have examined interactions between bioenergy and BECCS and other response options, the literature examining other combinations of response options is more limited.

6.4.4.3 Resolving challenges in response option implementation

The 40 response options assessed in this chapter face a variety of barriers to implementation that require action across multiple actors to overcome (Section 6.4.1). Studies have noted that, while adoption of response options by individuals may depend on individual assets and motivation, larger structural and institutional factors are almost always equally important if not more so (Adimassu et al. 2016; Djenontin et al. 2018), though harder to capture in research variables (Schwilch et al. 2014). These institutional and governance factors can create an enabling environment for sustainable land management (SLM) practices, or challenges to their adoption (Adimassu et al. 2013). Governance factors include the institutions that manage rules and policies, the social norms and collective actions of participants (including civil society actors and the private sector), and the interactions between them (Ostrom 1990; Huntjens et al. 2012; Davies 2016). Many of Ostrom's design principles for successful governance can be applied to response options for SLM; these principles are: (i) clearly defined boundaries, (ii) understanding of both benefits and costs, (iii) collective choice arrangements, (iv) monitoring, (v) graduated sanctions, (vi) conflict-resolution mechanisms, (vii) recognition of rights, and (viii) nested (multi-scale) approaches. Unfortunately, studies of many natural resources and land management policy systems – in particular, in developing countries – often show the opposite: a lack of flexibility, strong hierarchical tendencies, and a lack of local participation in institutional frameworks (Ampaire et al. 2017). Analysis of government effectiveness (GE) – defined as quality of public services, policy formulation and implementation, civil service and the degree of its independence from political pressures, as well as credibility of the government's commitment to its policies (Kaufmann et al. 2010) – has been shown to play a key role in land management. GE mediates land-user actions on land management and investment, and government policies and laws can help land users adopt sustainable land management practices (Nkonya et al. 2016) (Figure 6.9).

It is simply not a matter of putting the 'right' institutions or policies in place, however, as governance can be undermined by inattention to power dynamics (Fabinyi et al. 2014). Power shapes how actors gain access and control over resources, and negotiate, transform and adopt certain response options or not. These variable dynamics of power between different levels and stakeholders have an impact on the ability to implement different response options. The inability of many national governments to address social exclusion in general will have an effect on the implementation of many response options. Further, response options themselves can become avenues for actors to exert power claims over others (Nightingale 2017). For example, there have been many concerns that reduced deforestation and forest degradation projects run the risk of reversing trends towards decentralisation in forest management and creating new power disparities between the state and local actors (Phelps et al. 2010). Below we assess how two important factors – the involvement of stakeholders, and the coordination of action across scales – will help in moving from response options to policy implementation, a theme Chapter 7 takes up in further detail.

Involvement of stakeholders

A wide range of stakeholders are necessary for successful land, agricultural and environmental policy, and implementing response options requires that a range of actors, including businesses, consumers, land managers, indigenous peoples and local communities, scientists, and policymakers work together for success. Diverse stakeholders have a particularly important role to play in defining problems, assessing knowledge and proposing solutions (Stokes et al. 2006; Phillipson et al. 2012). Lack of connection between science knowledge and on-the-ground practice has hampered adoption of many response options in the past; simply presenting 'scientifically' derived response options is not enough (Marques et al. 2016). For example, the importance of recognising and incorporating local knowledge and indigenous knowledge is increasingly emphasised in successful policy implementation (see Cross-Chapter Box 13 in Chapter 7), as local practices of water management, soil fertility management, improved grazing, restoration and sustainable management of forests are often well-aligned with response options assessed by scientists (Marques et al. 2016).

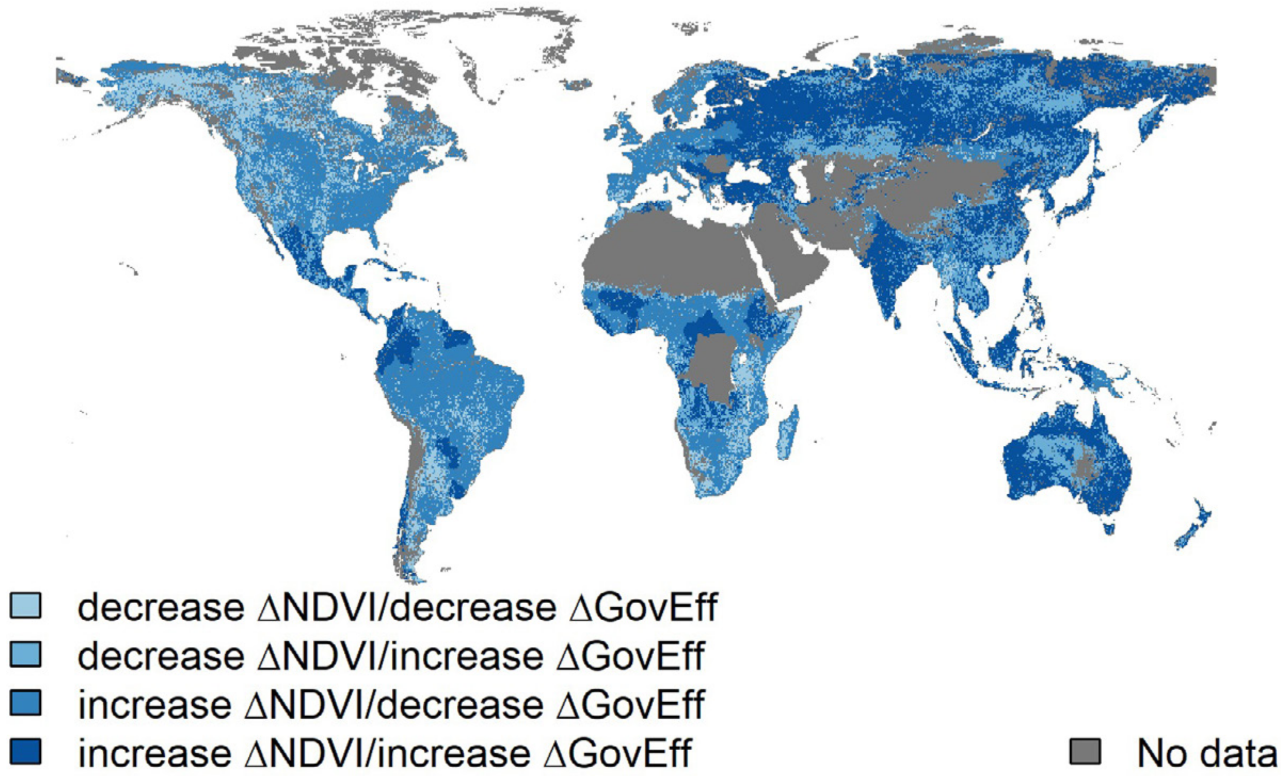

Figure 6.9 | Relationship between changes in government effectiveness (GE) and changes in land management. Notes: ΔNDVI = Change in Normalized Difference Vegetation Index (baseline year 2001, Endline year 2010). Source of NDVI data: MODIS ΔGovEff = Change in GE (baseline year 2001, endline year 2010). (World Bank; Nkonya et al. 2016).

Stakeholder engagement is an important approach for successful environmental and climate policy and planning. Tools such as stakeholder mapping, in which affected and interested parties are identified and described in terms of their interrelationships and current or future objectives and aspirations, and scenario-based stakeholder engagement, which combines stakeholder analysis with climate scenarios, are increasingly being applied to facilitate better planning outcomes (Tompkins et al. 2008; Pomeroy and Douvere 2008; Star et al. 2016). Facilitated dialogues early in design processes have shown good success in bringing multiple and sometimes conflicting stakeholders to the table to discuss synergies and trade-offs around policy implementation (Gopnik et al. 2012). Knowledge exchange, social learning, and other concepts are also increasingly being incorporated into understanding how to facilitate sustainable land management (Djenontin et al. 2018), as evidence suggests that negotiating the complexity of socio-ecological systems (SES) requires flexible learning arrangements, in particular for multiple stakeholders (Gerlak and Heikkila 2011; Armitage et al. 2018; Heikkila and Gerlak 2018). Social learning has been defined as 'a change in understanding and skills that becomes situated in groups of actors/communities of practice through social interactions,' (Albert et al. 2012), and social learning is often linked with attempts to increase levels of participation in decision-making, from consultation to more serious community control (Collins and Ison 2009; McCrum et al. 2009). Learning also facilitates responses to emerging problems and helps actors in SESs grapple with complexity. One outcome of learning can be adaptive risk management (ARM), in which 'one takes action based on available information, monitors what happens, learns from the experience and adjusts future actions based on what has been learnt' (Bidwell et al. 2013). Suggestions to facilitate social learning, ARM, and decision-making include extending science-policy networks and using local bridging organisations, such as extension services, for knowledge co-production (Bidwell et al. 2013; Böcher and Krott 2014; Howarth and Monasterolo 2017) (see further discussion in Chapter 7, Section 7.5).

Ensuring that women are included as key stakeholders in response option implementation is also important, as gender norms and roles affect vulnerability and access to resources, and gender inequality limits the possible range of responses for adoption by women (Lambrou and Piana 2006). For example, environmental change may increase women's workload as their access to natural resources may decline, or they may have to take up low-wage labour if agriculture becomes unsuitable in their local areas under climate change (Nelson et al. 2002). Every response option considered in this chapter potentially has a gender dimension to it that needs to be taken into consideration (Tables 6.73–6.75 note how response options intersect with SDG 5 Gender Equality); for example, to address food security through sustainable intensification will clearly have to address female farmers in Africa (Kondylis et al. 2016; Garcia and Wanner 2017) (for further information, see Cross-Chapter Box 11 in Chapter 7).

Challenges of coordination

Coordinated action to implement the response options will be required across a range of actors, including business, consumers, land managers, indigenous peoples and local communities and policymakers to create enabling conditions. Conjoining response options to maximise social, climatic and environmental benefits will require framing of such actions as strong pathways to sustainable development (Ayers and Dodman 2010). As the chapter has pointed out, there are many potential options for synergies, especially among several response options that might be applied together and in coordination with one another (such as dietary change and improved land management measures). This coordination will help ensure that synergies are met and trade-offs minimised, but this will require deliberate coordination across multiple scales, actors and sectors. For example, there are a variety of response options available at different scales that could form portfolios of measures applied by different stakeholders from farm to international scales. Agricultural diversification and use of local seeds by smallholders can be particularly useful poverty eradication and biodiversity conservation measures, but are only successful when higher scales, such as national and international markets and supply chains, also value these goods in trade regimes, and consumers see the benefits of purchasing these goods. However, the land and food sectors face particular challenges of institutional fragmentation, and often suffer from a lack of engagement between stakeholders at different scales (Biermann et al. 2009; Deininger et al. 2014) (see Chapter 7, Section 7.6.2).

Many of the response options listed in this chapter could be potentially implemented as 'community-based' actions, including community-based reforestation, community-based insurance, or community-based disaster risk management. Grounding response options in community approaches aims to identify, assist and implement activities 'that strengthen the capacity of local people to adapt to living in a riskier and less predictable climate' (Ayers and Forsyth 2009). Research shows that people willingly come together to provide mutual aid and protection against risk, to manage natural resources, and to work cooperatively to find solutions to environmental provisioning problems. Some activities that fall under this type of collective action include the creation of institutions or rules, working cooperatively to manage a resource by restricting some activities and encouraging others, sharing information to improve public goods, or mobilising resources (such as capital) to fix a collective problem (Ostrom 2000; Poteete and Ostrom 2004), or engagement in participatory land-use planning (Bourgoin 2012; Evers and Hofmeister 2011). These participatory processes 'are likely to lead to more beneficial environmental outcomes through better informed, sustainable decisions, and win-win solutions regarding economic and conservation objectives' (Vente et al. 2016), and evaluations of community-based response options have been generally positive (Karim and Thiel 2017; Tompkins and Adger 2004). Agrawal (2001) has identified more than 30 different indicators that have been important in understanding who undertakes collective action for the environment, including: the size of the group undertaking action; the type and distribution of the benefits from the action; the heterogeneity of the group; the dependence of the group on these benefits; the presence of leadership; presence of social capital and trust; and autonomy and independence to make and enforce rules. Alternatively, when households expect the government to undertake response actions, they have less incentive to join in collective action, as the state role has 'crowded out' local cooperation (Adger 2009). High levels of social trust and capital can increase willingness of farmers to engage in response options, such as improved soil management or carbon forestry (Stringer et al. 2012; Lee 2017), and social capital helps with connectivity across levels of SESs (Brondizio et al. 2009). Dietz et al. (2013) lay out important policy directions for more successful facilitation of collective action across scales and stakeholders. These include: providing information; dealing with conflict; inducing rule compliance; providing physical, technical or institutional infrastructure; and being prepared for change. The adoption of participatory protocols and structured processes to select response options together with stakeholders will likely lead to greater success in coordination and participation (Bautista et al. 2017; Franks 2010; Schwilch et al. 2012a).

However, wider adoption of community-based approaches is potentially hampered by several factors, including the fact that most are small-scale (Forsyth 2013; Ensor et al. 2014) and it is often unclear how to assess criteria of success (Forsyth 2013). Others also caution that community-based approaches often are not able to adequately address the key drivers of vulnerability such as inequality and uneven power relations (Nagoda and Nightingale 2017).

Moving from response options to policies

Chapter 7 discusses in further depth the risks and challenges involved in formulating policy responses that meet the demands for sustainable land management and development outcomes, such as food security, community adaptation and poverty alleviation. Table 7.1 in Chapter 7 maps how specific response options might be turned into policies; for example, to implement a response option aimed at agricultural diversification, a range of policies from elimination of agricultural subsidies (which might favour single crops) to environmental farm programmes and agro-environmental payments (to encourage alternative crops). Oftentimes, any particular response option might have a variety of potential policy pathways that might address different scales or stakeholders or take on different aspects of coordination and integration (Section 7.6.1). Given the unique challenges of decision-making under uncertainty in future climate scenarios, Chapter 7 particularly discusses the need for flexible, iterative, and adaptive processes to turn response options into policy frameworks.

Cross-Chapter Box 9 | Climate and land pathways

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Future development of socio-economic factors and policies influence the evolution of the land–climate system, among others, in terms of the land used for agriculture and forestry. Climate mitigation policies can also have a major impact on land use, especially in scenarios consistent with the climate targets of the Paris Agreement. This includes the use of bio-energy or CDR, such as bioenergy with carbon capture and storage (BECCS) and afforestation. Land-based mitigation options have implications for GHG fluxes, desertification, land degradation, food insecurity, ecosystem services and other aspects of sustainable development.

Shared Socio-economic Pathways

The five pathways are based on the Shared Socio-economic Pathways (SSPs) (O'Neill et al. 2014; Popp et al. 2017; Riahi et al. 2017; Rogelj et al. 2018b) (Cross-Chapter Box 1 in Chapter 1). SSP1 is a scenario with a broad focus on sustainability, including human development, technological development, nature conservation, globalised economy, economic convergence and early international cooperation (including moderate levels of trade). The scenario includes a peak and decline in population, relatively high agricultural yields and a move towards food produced in low-GHG emission systems (Van Vuuren et al. 2017b). Dietary change and reductions in food waste reduce agricultural demands, and effective land-use regulation enables reforestation and/or afforestation. SSP2 is a scenario in which production and consumption patterns, as well as technological development, follows historical patterns (Fricko et al. 2017). Land-based CDR is achieved through bioenergy and BECCS and, to a lesser degree, by afforestation and reforestation. SSP3 is a scenario with slow rates of technological change and limited land-use regulation. Agricultural demands are high due to material-intensive consumption and production, and barriers to trade lead to reduced flows for agricultural goods. In SSP3, forest mitigation activities and abatement of agricultural GHG emissions are limited due to major implementation barriers such as low institutional capacities in developing countries and delays as a consequence of low international cooperation (Fujimori et al. 2017). Emissions reductions are achieved primarily through the energy sector, including the use of bioenergy and BECCS.

Policies in the Pathways

SSPs are complemented by a set of shared policy assumptions (Kriegler et al. 2014), indicating the types of policies that may be implemented in each future world. Integrated Assessment Models (IAMs) represent the effect of these policies on the economy, energy system, land use and climate with the caveat that they are assumed to be effective or, in some cases, the policy goals (e.g., dietary change) are imposed rather than explicitly modelled. In the real world, there are various barriers that can make policy implementation more difficult (Section 7.4.9). These barriers will be generally higher in SSP3 than SSP1.

SSP1: A number of policies could support SSP1 in future, including: effective carbon pricing, emission trading schemes (including net CO_2 emissions from agriculture), carbon taxes, regulations limiting GHG emissions and air pollution, forest conservation (mix of land sharing and land sparing) through participation, incentives for ecosystem services and secure tenure, and protecting the environment, microfinance, crop and livelihood insurance, agriculture extension services, agricultural production subsidies, low export tax and import tariff rates on agricultural goods, dietary awareness campaigns, taxes on and regulations to reduce food waste, improved shelf life, sugar/fat taxes, and instruments supporting sustainable land management, including payment for ecosystem services, land-use zoning, REDD+, standards and certification for sustainable biomass production practices, legal reforms on land ownership and access, legal aid, legal education, including reframing these policies as entitlements for women and small agricultural producers (rather than sustainability) (Van Vuuren et al. 2017b; O'Neill et al. 2017) (Section 7.4).

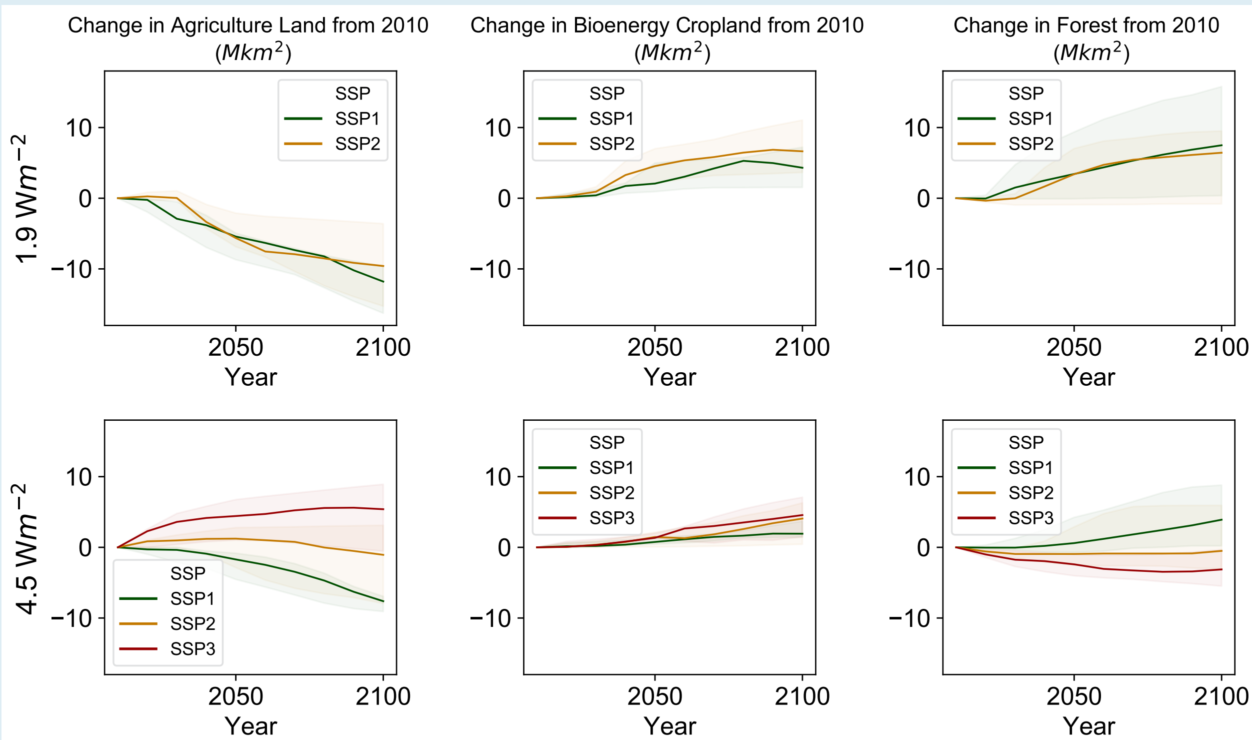
SSP2: The same policies that support SSP1 could support SSP2 but may be less effective and only moderately successful. Policies may be challenged by adaptation limits (Section 7.4.9), inconsistency in formal and informal institutions in decision-making (Section 7.5.1) or result in maladaptation (Section 7.4.7). Moderately successful sustainable land management policies result in some land competition. Land degradation neutrality is moderately successful. Successful policies include those supporting bioenergy and BECCS (Rao et al. 2017b; Fricko et al. 2017; Riahi et al. 2017) (Section 7.4.6).

SSP3: Policies that exist in SSP1 may or may not exist in SSP3, and are ineffective (O'Neill et al. 2014). There are challenges to implementing these policies, as in SSP2. In addition, ineffective sustainable land management policies result in competition for land between agriculture and mitigation. Land degradation neutrality is not achieved (Riahi et al. 2017). Successful policies include those supporting bioenergy and BECCS (Kriegler et al. 2017; Fujimori et al. 2017; Rao et al. 2017b) (Section 7.4.6). Demand-side food policies are absent and supply-side policies predominate. There is no success in advancing land ownership and access policies for agricultural producer livelihood (Section 7.6.5).

Cross-Chapter Box 9 (continued)

Land-use and land-cover change

In SSP1, sustainability in land management, agricultural intensification, production and consumption patterns result in reduced need for agricultural land, despite increases in per capita food consumption. This land can instead be used for reforestation, afforestation and bioenergy. In contrast, SSP3 has high population and strongly declining rates of crop yield growth over time, resulting in increased agricultural land area. SSP2 falls somewhere in between, with societal as well as technological development following historical patterns. Increased demand for land mitigation options such as bioenergy, reduced deforestation or afforestation decreases availability of agricultural land for food, feed and fibre. In the climate policy scenarios consistent with the Paris Agreement, bioenergy/BECCS and reforestation/afforestation play an important role in SSP1 and SSP2. The use of these options, and the impact on land, is larger in scenarios that limit radiative forcing in 2100 to 1.9 W m^{-2} than in the 4.5 W m^{-2} scenarios. In SSP3, the expansion of land for agricultural production implies that the use of land-related mitigation options is very limited, and the scenario is characterised by continued deforestation.



Cross-Chapter Box 9, Figure 1 | Changes in agriculture land (left), bioenergy cropland (middle) and forest (right) under three different SSPs (colours) and two different warming levels (rows). Agricultural land includes both pasture and cropland. Colours indicate SSPs, with SSP1 shown in green, SSP2 in yellow, and SSP3 in red. For each pathway, the shaded areas show the range across all IAMs; the line indicates the median across models. There is no SSP3 in the top row, as 1.9 W m^{-2} is infeasible in this world. Data is from an update of the Integrated Assessment Modelling Consortium (IAMC) Scenario Explorer developed for the SR15 (Huppmann et al. 2018; Rogelj et al. 2018a).

Implications for mitigation and other land challenges

The combination of baseline emissions development, technology options, and policy support makes it much easier to reach the climate targets in the SSP1 scenario than in the SSP3 scenario. As a result, carbon prices are much higher in SSP3 than in SSP1. In fact, the 1.9 W m^{-2} target was found to be infeasible in the SSP3 world (Table 1 in Cross-Chapter Box 9). Energy system CO_2 emissions reductions are greater in SSP3 than in SSP1 to compensate for the higher land-based CO_2 emissions.

Accounting for mitigation and socio-economics alone, food prices (an indicator of food insecurity) are higher in SSP3 than in SSP1 and higher in the 1.9 W m^{-2} target than in the 4.5 W m^{-2} target (Table 1 in Cross-Chapter Box 9). Forest cover is higher in SSP1 than SSP3 and higher in the 1.9 W m^{-2} target than in the 4.5 W m^{-2} target. Water withdrawals and water scarcity are, in general, higher in SSP3 than SSP1 (Hanasaki et al. 2013; Graham et al. 2018) and higher in scenarios with more bioenergy (Hejazi et al. 2014b); however, these indicators have not been quantified for the specific SSP-representative concentration pathways (RCP) combinations discussed here.

Cross-Chapter Box 9 (continued)

Cross-Chapter Box 9, Table 1 | Quantitative indicators for the pathways. Each cell shows the mean, minimum, and maximum value across IAM models for each indicator and each pathway in 2050 and 2100. All IAMs that provided results for a particular pathway are included here. Note that these indicators exclude the implications of climate change. Data is from an update of the IAMC Scenario Explorer developed for the SR15 (Huppmann et al. 2018; Rogelj et al. 2018b).

		SSP1		SSP2		SSP3	
		1.9 W m^{-2} mean (max., min.)	4.5 W m^{-2} mean (max., min.)	1.9 W m^{-2} mean (max., min.)	4.5 W m^{-2} mean (max., min.)	1.9 W m^{-2} mean (max., min.)	4.5 W m^{-2} mean (max., min.)
Population (billion)	2050	8.5 (8.5, 8.5)	8.5 (8.5, 8.5)	9.2 (9.2, 9.2)	9.2 (9.2, 9.2)	N/A	10.0 (10.0, 10.0)
	2100	6.9 (7.0, 6.9)	6.9 (7.0, 6.9)	9.0 (9.0, 9.0)	9.0 (9.1, 9.0)	N/A	12.7 (12.8, 12.6)
Change in GDP per capita (% rel to 2010)	2050	170.3 (380.1, 130.9)	175.3 (386.2, 166.2)	104.3 (223.4, 98.7)	110.1 (233.8, 103.6)	N/A	55.1 (116.1, 46.7)
	2100	528.0 (1358.4, 408.2)	538.6 (1371.7, 504.7)	344.4 (827.4, 335.8)	356.6 (882.2, 323.3)	N/A	71.2 (159.7, 49.6)
Change in forest cover (Mkm^2)	2050	3.4 (9.4, -0.1)	0.6 (4.2, –0.7)	3.4 (7.0, –0.9)	–0.9 (2.9, –2.5)	N/A	–2.4 (–1.0, –4.0)
	2100	7.5 (15.8, 0.4)	3.9 (8.8, 0.2)	6.4 (9.5, –0.8)	–0.5 (5.9, –3.1)	N/A	–3.1 (–0.3, –5.5)
Change in cropland (Mkm^2)	2050	–1.2 (–0.3, –4.6)	0.1 (1.5, –3.2)	–1.2 (0.3, –2.0)	1.2 (2.7, –0.9)	N/A	2.3 (3.0, 1.2)
	2100	–5.2 (–1.8, –7.6)	–2.3 (–1.6, –6.4)	–2.9 (0.1, –4.0)	0.7 (3.1, –2.6)	N/A	3.4 (4.5, 1.9)
Change in energy cropland (Mkm^2)	2050	2.1 (5.0, 0.9)	0.8 (1.3, 0.5)	4.5 (7.0, 2.1)	1.5 (2.1, 0.1)	N/A	1.3 (2.0, 1.3)
	2100	4.3 (7.2, 1.5)	1.9 (3.7, 1.4)	6.6 (11.0, 3.6)	4.1 (6.3, 0.4)	N/A	4.6 (7.1, 1.5)
Change in pasture (Mkm^2)	2050	–4.1 (–2.5, –5.6)	–2.4 (–0.9, –3.3)	–4.8 (–0.4, –6.2)	–0.1 (1.6, –2.5)	N/A	2.1 (3.8, –0.1)
	2100	–6.5 (–4.8, –12.2)	–4.6 (–2.7, –7.3)	–7.6 (–1.3, –11.7)	–2.8 (1.9, –5.3)	N/A	2.0 (4.4, –2.5)
Change in other natural land (Mkm^2)	2050	0.5 (1.0, –4.9)	0.5 (1.7, –1.0)	–2.2 (0.6, –7.0)	–2.2 (0.7, –2.2)	N/A	–3.4 (–2.0, –4.4)
	2100	0.0 (7.1, –7.3)	1.8 (6.0, –1.7)	–2.3 (2.7, –9.6)	–3.4 (1.5, –4.7)	N/A	–6.2 (–5.4, –6.8)
Carbon price (2010 USD per tCO$_2$)[a]	2050	510.4 (4304.0, 150.9)	9.1 (35.2, 1.2)	756.4 (1079.9, 279.9)	37.5 (73.4, 13.6)	N/A	67.2 (75.1, 60.6)
	2100	2164.0 (350, 37.7, 262.7)	64.9 (286.7, 42.9)	4353.6 (10149.7, 2993.4)	172.3 (597.9, 112.1)	N/A	589.6 (727.2, 320.4)
Food price (Index 2010=1)	2050	1.2 (1.8, 0.8)	0.9 (1.1, 0.7)	1.6 (2.0, 1.4)	1.1 (1.2, 1.0)	N/A	1.2 (1.7, 1.1)
	2100	1.9 (7.0, 0.4)	0.8 (1.2, 0.4)	6.5 (13.1, 1.8)	1.1 (2.5, 0.9)	N/A	1.7 (3.4, 1.3)
Increase in Warming above pre-industrial (°C)	2050	1.5 (1.7, 1.5)	1.9 (2.1, 1.8)	1.6 (1.7, 1.5)	2.0 (2.0, 1.9)	N/A	2.0 (2.1, 2.0)
	2100	1.3 (1.3, 1.3)	2.6 (2.7, 2.4)	1.3 (1.3, 1.3)	2.6 (2.7, 2.4)	N/A	2.6 (2.6, 2.6)
Change in per capita demand for food, crops (% rel to 2010)[b]	2050	6.0 (10.0, 4.5)	9.1 (12.4, 4.5)	4.6 (6.7, –0.9)	7.9 (8.0, 5.2)	N/A	2.4 (5.0, 2.3)
	2100	10.1 (19.9, 4.8)	15.1 (23.9, 4.8)	11.6 (19.2, –10.8)	11.7 (19.2, 4.1)	N/A	2.0 (3.4, –1.0)
Change in per capita demand for food, animal products (% rel to 2010)[b,c]	2050	6.9 (45.0, –20.5)	17.9 (45.0, –20.1)	7.1 (36.0, 1.9)	10.3 (36.0, –4.2)	N/A	3.1 (5.9, 1.9)
	2100	–3.0 (19.8, –27.3)	21.4 (44.1, –26.9)	17.0 (39.6, –24.1)	20.8 (39.6, –5.3)	N/A	–7.4 (–0.7, –7.9)
Agriculture, forestry and other land-use (AFOLU) CH_4 Emissions (% relative to 2010)	2050	–39.0 (–3.8, –68.9)	–2.9 (22.4, –23.9)	–11.7 (31.4, –59.4)	7.5 (43.0, –15.5)	N/A	15.0 (20.1, 3.1)
	2100	–60.5 (–41.7, –77.4)	–47.6 (–24.4, –54.1)	–40.3 (33.1, –58.4)	–13.0 (63.7, –45.0)	N/A	8.0 (37.6, –9.1)
AFOLU N_2O Emissions (% relative to 2010)	2050	–13.1 (–4.1, –26.3)	0.1 (34.6, –14.5)	8.8 (38.4, –14.5)	25.4 (37.4, 5.5)	N/A	34.0 (50.8, 29.3)
	2100	–42.0 (4.3, –49.4)	–25.6 (–3.4, –51.2)	–1.7 (46.8, –37.8)	19.5 (66.7, –21.4)	N/A	53.9 (65.8, 30.8)
Cumulative Energy CO_2 Emissions until 2100 ($GtCO_2$)		428.2 (1009.9, 307.6)	2787.6 (3213.3, 2594.0)	380.8 (552.8, –9.4)	2642.3 (2928.3, 2515.8)	N/A	2294.5 (2447.4, 2084.6)
Cumulative AFOLU CO_2 Emissions until 2100 ($GtCO_2$)		–127.3 (5.9, –683.0)	–54.9 (52.1, –545.2)	–126.8 (153.0, –400.7)	40.8 (277.0, –372.9)	N/A	188.8 (426.6, 77.9)

[a] SSP2–19 is infeasible in two models. One of these models sets the maximum carbon price in SSP1–19; the carbon price range is smaller for SSP2–19 as this model is excluded there. Carbon prices are higher in SSP2–19 than SSP1–19 for every model that provided both simulations.

[b] Food demand estimates include waste.

[c] Animal product demand includes meat and dairy.

6

Cross-Chapter Box 9 (continued)

Climate change results in higher impacts and risks in the 4.5 W m^{-2} world than in the 1.9 W m^{-2} world for a given SSP and these risks are exacerbated in SSP3 compared to SSP1 and SSP2 due to the population's higher exposure and vulnerability. For example, the risk of fire is higher in warmer worlds; in the 4.5 W m^{-2} world, the population living in fire prone regions is higher in SSP3 (646 million) than in SSP2 (560 million) (Knorr et al. 2016). Global exposure to multi-sector risk quadruples between 1.5°C[11] and 3°C and is a factor of six higher in SSP3-3°C than in SSP1–1.5°C (Byers et al. 2018). Future risks resulting from desertification, land degradation and food insecurity are lower in SSP1 compared to SSP3 at the same level of warming. For example, the transition moderate-to-high risk of food insecurity occurs between 1.3 and 1.7°C for SSP3, but not until 2.5 to 3.5°C in SSP1 (Section 7.2).

Summary

Future pathways for climate and land use include portfolios of response and policy options. Depending on the response options included, policy portfolios implemented, and other underlying socio-economic drivers, these pathways result in different land-use consequences and their contribution to climate change mitigation. Agricultural area declines by more than 5 Mkm^2 in one SSP but increases by as much as 5 Mkm^2 in another. The amount of energy cropland ranges from nearly zero to 11 Mkm^2, depending on the SSP and the warming target. Forest area declines in SSP3 but increases substantially in SSP1. Subsequently, these pathways have different implications for risks related to desertification, land degradation, food insecurity, and terrestrial GHG fluxes, as well as ecosystem services, biodiversity, and other aspects of sustainable development.

6.4.5 Potential consequences of delayed action

Delayed action, in terms of overall GHG mitigation across both land and energy sectors, as well as delayed action in implementing the specific response options outlined in this chapter, will exacerbate the existing land challenges due to the continued impacts of climate change and socio-economic and other pressures. It can decrease the potential of response options and increase the costs of deployment, and will deprive communities of immediate co-benefits, among other pressures. The major consequences of delayed action are outlined below.

Delayed action exposes vulnerable people to continued and increasing climate impacts: Slower or delayed action in implementing response options exacerbates existing inequalities and impacts. This will increase the number of people vulnerable to climate change, due to population increases and increasing climate impacts (IPCC 2018; AR 5). Future climate change will lead to exacerbation of the existing land challenges, increased pressure on agricultural livelihoods, potential for rapid land degradation, and millions more people exposed to food insecurity (Schmidhuber and Tubiello 2007) (Chapters 3, 4 and 5). Delay can also bring political risks and significant social impacts, including risks to human settlements (particularly in coastal areas), large-scale migration, and conflict (Barnett and Adger 2007; Hsiang et al. 2013). Early action reducing vulnerability and exposure can create an opportunity for a virtual circle of benefits: increased resilient livelihoods, reduced degradation of land, and improved food security (Bohle et al. 1994).

Delayed action increases requirements for adaptation: Failure to mitigate climate change will increase requirements for adaptation. For example, it is likely that by 2100 with no mitigation or adaptation, 31–69 million people world-wide could be exposed to flooding (Rasmussen et al. 2017; IPCC SR15) (Chapter 3); such outcomes could be prevented with investments in both mitigation and adaptation now. Some specific response options (e.g., reduced deforestation and forest degradation, reduced peatland and wetland conversion) prevent further detrimental effects to the land surface; delaying these options could lead to increased deforestation, conversion, or degradation, serving as increased sources of GHGs and having concomitant negative impacts on biodiversity and ecosystem services (Section 6.2). Response options aimed at land restoration and rehabilitation can serve as adaptation mechanisms for communities facing climatic stresses like precipitation variability and changes in land quality, as well as provide benefits in terms of mitigation.

Delayed action increases response costs and reduces economic growth: Early action on reducing emissions through mitigation is estimated to result in smaller temperature increases as well as lower mitigation costs than delayed action (Sanderson et al. 2016; Luderer et al. 2013, 2018; Rose et al. 2017; Van Soest et al. 2017; Fujimori et al. 2017). The cost of inaction to address mitigation, adaptation, and sustainable land use exceeds the cost of immediate action in most countries, depending on how damage functions and the social cost of carbon are calculated (Dell et al. 2012; Moore and Diaz 2015). Costs of acting now would be one to two orders of magnitude lower than economic damages from delayed action, including damage to assets from climate impacts, as well as potentially reduced economic growth, particularly in developing countries (Luderer et al. 2016; Moore and Diaz 2015; Luderer et al. 2013). Increased health costs and costs of energy (e.g., to run air-conditioners to combat increased heat waves) in the US by the end of the century alone are estimated to range from 10–58% of US GDP in 2010 (Deschênes and Greenstone 2011).

11 Pathways that limit radiative forcing in 2100 to 1.9 W m^{-2} result in median warming in 2100 to 1.5°C in 2100 (Rogelj et al. 2018b). Pathways limiting radiative forcing in 2100 to 4.5 W m^{-2} result in median warming in 2100 above 2.5°C (IPCC 2014).

Delay also increases the costs of both mitigation and adaptation actions at later dates. In models of climate-economic interactions, deferral of emissions reduction now requires trade-offs leading to higher costs of several orders of magnitude and risks of higher temperatures in the longer term (Luderer et al. 2013). Further, the cost of action is likely to increase over time due to the increased severity of challenges in future scenarios.

Conversely, timely implementation of response options brings economic benefits. Carbon pricing is one economic component to encourage adoption of response options (Jakob et al. 2016), but carbon pricing alone can induce higher risk in comparison to other scenarios and pathways that include additional targeted sustainability measures, such as promotion of less material- and energy-intensive lifestyles and healthier diets, as noted in our response options (Bertram et al. 2018). While the short-term costs of deployment of actions may increase, better attainment of a broad set of sustainability targets can be achieved through these combined measures (Bertram et al. 2018).

There are also investments now that can lead to immediate savings in terms of avoided damages; for example, for each dollar spent on disaster risk management, countries accrue avoided disaster-related economic losses of 4 USD or more (Mechler 2016). While they can require upfront investment, the economic benefits of actions to ensure sustainable land management, such as increased soil organic carbon, can more than double the economic value of rangelands and improve crop yields (Chapter 4 and Section 6.2).

Delayed action reduces future policy space and decreases efficacy of some response options: The potential for some response options decreases as climate change increases; for example, climate alters the sink capacity for soil and vegetation carbon sequestration, reducing the potential for increased soil organic carbon, afforestation and reforestation (Section 6.4.2). Additionally, climate change affects the productivity of bioenergy crops, influencing the potential mitigation of bioenergy and BECCS (Section 6.4.4).

For response options in the supply chain, demand-side management, and risk management, while the consequences of delayed action are apparent in terms of continued GHG emissions from drivers, the tools for response options are not made more difficult by delay and could be deployed at any time. Additionally, given increasing pressures on land as a consequence of delay, some policy response options may become more cost-effective while others become costlier. For example, over time, land-based mitigation measures like forest and ecosystem protection are likely to increase land scarcity, leading to higher food prices; while demand-side measures, like reduced-impact diets and reducing waste, are less likely to raise food prices in economic models (Stevanović et al. 2017).

For risk management, some response options provide timely and rapidly deployable solutions for preventing further problems, such as disaster risk management and risk-sharing instruments. For example, early warning systems serve multiple roles in protecting lives and property and helping people adapt to longer-term climate changes, and can be used immediately.

Delaying action can also result in problems of irreversibility of biophysical impacts and tipping points: Early action provides a potential way to avoid irreversibility – such as degradation of ecosystems that cannot be restored to their original baseline – and tipping points, whereby ecological or climate systems abruptly shift to a new state. Ecosystems, such as peatlands, are particularly vulnerable to irreversibility because of the difficulties of rewetting to original states (Section 6.2), and dryland grazing systems are vulnerable to tipping points when ground cover falls below 50%, after which productivity falls, infiltration declines, and erosion increases (Chapters 3 and 4). Further, tipping points can be especially challenging for human populations to adapt to, given the lack of prior experience with such system shifts (Kates et al. 2012; Nuttall 2012).

Policy responses require lead time for implementation; delay makes this worse: For all the response options, particularly those that need to be deployed through policy implementation, there are unavoidable lags in this cycle. 'Policy lags', by which implementation is delayed by the slowness of the policy implementation cycle, are significant across many land-based, response options (Brown et al. 2019). Further, the behavioural change necessary to achieve some demand-side and risk management response options often takes a long time, and delay only lengthens this process (Stern 1992; Steg and Vlek 2009). For example, actively promoting the need for healthier and more sustainable diets through individual dietary decisions is an important underpinning and enabling step for future changes, but is likely to be a slow-moving process, and delay in beginning will only exacerbate this.

Delay can lead to lock-in: Delay in implementation can cause 'lock-in' as decisions made today can constrain future development and pathways. For example, decisions made now on where to build infrastructure, make investments and deploy technologies, will have longer-term (decades-long) ramifications due to the inertia of capital stocks (Van Soest et al. 2017). In tandem, the vulnerability of the poor is likely to be exacerbated by climate change, creating a vicious circle of lock in whereby an increasing share of the dwindling carbon budget may be needed to assist with improved energy use for the poorest (Lamb and Rao 2015).

Delay can increase the need for widespread deployment of land-based mitigation (afforestation, BECCS) (IPCC 2018; Strefler et al. 2018): Further delays in mitigation could result in an increased need for carbon dioxide removal (CDR) options later; for example, delayed mitigation requires a 10% increase in cumulative CDR over the century (IPCC 2018). Similarly, strengthening near-term mitigation effort can reduce the CDR requirements in 2100 by a factor of 2 to 8 (Strefler et al. 2018). Conversely, scenarios with limited CDR require earlier emissions reductions (Van Vuuren et al. 2017b) and may make more stringent mitigation scenarios, like the 1.5°C, infeasible (Kriegler et al. 2018a,b).

Frequently Asked Questions

FAQ 6.1 | What types of land-based options can help mitigate and adapt to climate change?

Land-based options that help mitigate climate change are various and differ greatly in their potential. The options with moderate-to-large mitigation potential, and no adverse side effects, include options that decrease pressure on land (e.g., by reducing the land needed for food production) and those that help to maintain or increase carbon stores both above-ground (e.g., forest measures, agroforestry, fire management) and below-ground (e.g., increased soil organic matter or reduced losses, cropland and grazing land management, urban land management, reduced deforestation and forest degradation). These options also have co-benefits for adaptation by improving health, increasing yields, flood attenuation and reducing urban heat island effects. Another group of practices aim at reducing greenhouse gas (GHG) emission sources, such as livestock management or nitrogen fertilisation management. Land-based options delivering climate change adaptation may be structural (e.g., irrigation and drainage systems, flood and landslide control), technological (e.g., new adapted crop varieties, changing planting zones and dates, using climate forecasts), or socio-economic and institutional (e.g., regulation of land use, associativity between farmers). Some adaptation options (e.g., new planting zones, irrigation) may have adverse side effects for biodiversity and water. Adaptation options may be planned, such as those implemented at regional, national or municipal level (top-down approaches), or autonomous, such as many technological decisions taken by farmers and local inhabitants. In any case, their effectiveness depends greatly on the achievement of resilience against extreme events (e.g., floods, droughts, heat waves, etc.).

FAQ 6.2 | Which land-based mitigation measures could affect desertification, land degradation or food security?

Some options for mitigating climate change are based on increasing carbon stores, both above-ground and below-ground, so mitigation is usually related to increases in soil organic matter content and increased land cover by perennial vegetation. There is a direct relationship, with very few or no adverse side effects for prevention or reversal of desertification and land degradation and the achievement of food security. This is because desertification and land degradation are closely associated with soil organic matter losses and the presence of bare ground surfaces. Food security depends on the achievement of healthy crops and high and stable yields over time, which is difficult to achieve in poor soils that are low in organic matter.

FAQ 6.3 | What is the role of bioenergy in climate change mitigation, and what are its challenges?

Plants absorb carbon as they grow. If plant-based material (biomass) is used for energy, the carbon it absorbed from the atmosphere is released back. Traditional use of bioenergy for cooking and heating is still widespread throughout the world. Modern conversion to electricity, heat, gas and liquid fuels can reduce the need to burn fossil fuels and this can reduce GHG emissions, helping to mitigate climate change. However, the total amount of emissions avoided depends on the type of biomass, where it is grown, how it is converted to energy, and what type of energy source it displaces. Some types of bioenergy require dedicated land (e.g., canola for biodiesel, perennial grasses, short rotation woody crops), while others can be co-produced or use agricultural or industrial residues (e.g., residues from sugar and starch crops for ethanol, and manure for biogas). Depending on where, how, and the amount of bioenergy crops that are grown, the use of dedicated land for bioenergy could compete with food crops or other mitigation options. It could also result in land degradation, deforestation or biodiversity loss. In some circumstances, however, bioenergy can be beneficial for land, for example, by increasing soil organic carbon. The use of co-products and residues for bioenergy limits the competition for land with food but could result in land degradation if carbon and nutrient-rich material is removed that would otherwise be left on the land. On the other hand, the by-products of some bioenergy conversion processes can be returned to the land as a fertiliser and may have other co-benefits (e.g., reducing pollution associated with manure slurry).

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