Chapter 6: Interlinkages between Desertification, Land Degradation, Food Security and GHG fluxes: synergies, trade-offs and Integrated Response Options

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6.1 Executive summary

Response options have interlinked implications across the land challenges of mitigation, adaptation, desertification, land degradation and food security; options to address one land challenge may also help to address others, or can exacerbate other problems (*robust evidence; high agreement*) {Sections 6.3–6.4}. Among the response options available to address the land challenges of mitigation, adaptation, desertification, land degradation and food security, many have impacts across more than one challenge. Some response options deliver co-benefits across a range of challenges; for example many sustainable land management practices co-deliver benefits to climate change mitigation and adaptation, preventing or addressing desertification and land degradation, and food security (*robust evidence; high agreement*) {Section 6.5}. Other response options create adverse-side effects for one or more challenges, for example response options that demand land for climate mitigation could cause adverse side effects if implemented at scale for food production and thereby food security, *via* increasing competition for land (*robust evidence; high agreement*) {Sections 6.3, 6.4, 6.5}.

Land resources are limited. Competition for land may restrict the scale at which response options can be used (*robust evidence; high agreement*). Land is a finite resource and expansion of the current area of managed land into natural ecosystems would lead to the loss of biodiversity and a range of Nature's Contributions to People (*robust evidence; high agreement*) {Section 6.5}. For this reason, the scale at which some response options can be applied is limited, with response options that compete for land, for example, afforestation, BECCS, most affected (*robust evidence; high agreement*) {Section 6.4, 6.5}. Other options that can be applied without changing the use of the land, for example measures to increase the soil organic matter (carbon) content of soils, are not limited by land competition constraints (*robust evidence; high agreement*) {Section 6.5}.

The impacts of many response options are scale and context dependent, and are uneven across different regions and communities (*robust evidence; high agreement*) {Sections 6.4–6.5}. The efficacy and impacts of response options to address each land challenge is location specific, with for example, the mitigation effectiveness or adaptation effectiveness differing by bioclimatic region, land management system or local food system context (*robust evidence; high agreement*) {Sections 6.3, 6.5}. Further, for some scalable response options, large global impacts are seen only when implemented at large scale {Sections 6.4, 6.5}. In addition, impacts are context dependent, with certain options producing adverse side-effects only in certain locations, for example response options that use freshwater might have no adverse side effects in regions where water is plentiful, but large adverse side effects in regions where water is scarce (*robust evidence; high agreement*) {Section 6.5}.

All land challenges need to be considered when addressing potential solutions, in order to identify response options that co-deliver across the range of challenges (*robust evidence; high agreement*) {Section 6.3}. Because the different land challenges are often the concern of different policy and research communities, response options are often proposed to address a specific land challenge. However, since all land challenges share the same land resource, response options can affect, positively or negatively, a number of land challenges {Section 6.3}. For this reason, considering the impact of response options on all land challenges simultaneously will allow co-benefits to be maximised and adverse side-effects to be minimised (*medium evidence; high agreement*) {Section 6.5}.

Many response options (over 40 in number) have multiple co-benefits across land-related goals, but some are not currently widely implemented (*robust evidence; high agreement*) {Section 6.4, 6.5}. The majority of response options considered have potential to deliver co-benefits across the range of land challenges, with co-benefits ranging from large to small across options and challenges (*robust evidence; high agreement*) {Section 6.5}. Other options deliver large co-benefits for one or two challenges, with negligible impact on others, but do no harm. Many of the same options also have either no, or small, context-specific adverse side-effects (*robust evidence; high agreement*) {Section 6.5}.

There are, therefore, a range of “no regrets” or “low regrets” options that are suitable for wider implementation to address multiple land challenges. While some of these response options are implemented widely in some regions, other are not, and even for those with wide regional adoption, there is considerable scope for wider deployment globally (*robust evidence; high agreement*) {Section 6.5}.

Some response options, such as large-scale BECCS, have the potential to deliver very well for one land challenge only, with potential detrimental effects on other land challenges (*robust evidence; high agreement*) {Section 6.4, 6.5}. A small number response options have very large potential to address one land challenge, but could lead to large adverse side-effects if implemented at scale. Options that require land use change (e.g., BECCS, afforestation), and thereby contribute to land competition, are most prevalent in this category, with food security the land challenge most often adversely affected (*robust evidence; high agreement*) {Section 6.5}. Options that improve land management or improve efficiency of production of food and fibre (sustainable land management options) do not fall into this category and they either do not affect competition for land, or have the potential to decrease it (*robust evidence; high agreement*) {Section 6.5}.

There are currently barriers to implementation for many response options; identifying and removing barriers is necessary to make progress toward sustainable solutions (*robust evidence; high agreement*) {Section 6.5}. Since there is good evidence that many response options will deliver multiple co-benefits across the range of land challenges, yet these are not applied universally, is evidence that multiple barriers to implementation exist (*robust evidence; high agreement*) {Section 6.5}. A combination of economic, biophysical, technological, institutional, education, cultural and behavioural barriers exist for each response option in various regions, and these barriers need to be overcome if response options are to be more widely applied (*robust evidence; high agreement*) {Section 6.5}. Options aiming to preserve ecosystem services and biodiversity depend largely on land governance and financial aid, since markets where such services can be traded are not well developed. Improved institutional frameworks would strengthen land governance and facilitate efforts to preserve ecosystem services and biodiversity (*medium evidence; high agreement*) {Section 6.5}.

Coordinated action is required across a range of actors, including business, consumers, land managers, indigenous and local communities and policymakers (*robust evidence; high agreement*) {Section 6.5}. Since barriers to implementation are economic, biophysical, technological, institutional, education, cultural and behavioural, action is required across a multiple actors (*robust evidence; high agreement*) {Section 6.5}. Because of the wide range of actors, and the wide range of impacts to be considered across the land challenges, action to address barriers to implementation would be most effective if action were coordinated across the range of actors, including business, consumers, land managers, indigenous and local communities and policymakers (*robust evidence; high agreement*) {Section 6.5}.

The need to act is urgent. Delayed action will result in an increased need for response and a decreased potential of response options due to climate change and other pressures (*robust evidence; high agreement*) {Section 6.5}. Delayed action to address any of the land challenges of climate change, desertification, land degradation and food security make the challenges more difficult to address in future, and often make the response options less effective. For example, failure to mitigate climate change with increase requirements for adaptation, and may reduce the efficacy of future mitigation options, for example, by reducing the sink capacity for soil and vegetation carbon sequestration (*robust evidence; high agreement*) {Section 6.3}. For this reason, and the extent of the land challenges currently, the need to act is urgent (*robust evidence; high agreement*) {Section 6.5}.

Though there are gaps in knowledge and more R&D is required for many response options, enough is known to take action now (*robust evidence; high agreement*) {Section 6.5}. There are knowledge gaps for some response options, both in their efficacy and in their broader impacts, particularly among the more recently emerging options (e.g., enhanced weathering of minerals, BECCS; (*robust evidence; high agreement*) {Section 6.3, 6.4}. Nevertheless, many response options have been practiced in some regions for many years and have a broad evidence base, so could be applied more widely immediately, with little risk of adverse side-effects if the best available knowledge is used to design implementation plans for these "no regrets" / "low regrets" options (*robust evidence; high agreement*) {Section 6.5}.

Cost-effective no / low regrets options are available for immediate local application, providing that compliance with sustainable development is considered (*robust evidence; high agreement*) {Section 6.5}. Many "no regrets" response options which deliver across the range of land challenges and beyond (e.g., improved dietary health through improved diets) are also cost-effective, with many being low cost, and some even cost negative (*robust evidence; high agreement*) {Section 6.5}. Where not already applied due to local barriers to implementation, these response options are available for immediate application, if barriers can be removed. Assessing impacts against the Sustainable Development Goals (and indicators thereof), or other components of sustainable development, would provide a safeguard against inappropriate local implementation (*medium evidence; high agreement*) {Section 6.5}.

Creating an enabling environment, including local engagement, to facilitate the adoption of no-regrets options is required (*robust evidence; high agreement*) {Section 6.5}. In addition to the need to engage multiple actors, and to assess the impact of implementation across the range of land challenges and against compliance with sustainable development, implementation of response options would be facilitated by local engagement, and the creation of an enabling environment under which the barriers to implementation could be overcome (*medium evidence; high agreement*) {Section 6.2; 6.5}. Policy will require to address all of these issues (*medium evidence; high agreement*) {Section 6.5; Chapter 7}.

6.2 Introduction

6.2.1 Context of this chapter

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

Since we aim to assess and provide guidance on integrative response options, we first describe and categorise the integrative response options (Section 6.3), we then quantify their impact on climate mitigation / adaptation, prevention or reversal of desertification, prevention or reversal of land degradation, and food security (Section 6.4), before providing the *co-benefits* and *adverse side-effects*[b] of each integrative response option across the five land challenges, and their impacts on the NCPs and the SDGs (6.5). We then examine the spatial applicability of these integrative response options in relation to the location of the challenges, we assess the barriers to implementation, and discuss the enabling conditions that could address these barriers. The aim of the final Section (6.5) is to identify which options have the greatest potential to co-deliver across the challenges, and the contexts and circumstances in which they do so.

In providing this evidence-based assessment, drawing on the relevant literature, we do 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 we provide a list of integrated response options that are best able to co-deliver across the multiple challenges addressed in this SR.

6.2.2 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 seen as solely 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 sustainable development goals, but which have not resulted in major shifts in implementation; for example, online databases of multiple response options have been compiled by many donor agencies (Schwilch et al.,2012). 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

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[a] Footnote: Many of the response options considered are *sustainable land management* options, but a few response options are not based on land management, for example those based on value chain management and governencae and risk management options

[b] Footnote: We use the IPCC AR5 WGIII definitions of co-benefits and adverse side-effect – see glossary. Though many of the co-benefits and adverse side-effects are biophysical, some are socio-economic in nature, and these are also assessed.

factors (Nigussie et al.,2017; Dallimer et al. 2018) While a useful approach, such studies often are unable to account for the larger enabling factors that might assist in more wide scale implementation.

Instead, this chapter proposes that each response option identified and assessed needs to be understood as an intervention within complex socio-ecological systems (SES), which are place-specific and multi-scalar frameworks of interactions between unique ecological and social contexts) (Brunson, 2012; Reid et al. 2014; Leslie et al.,2015). 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 et al.,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 42 specific response options in this chapter, it must be kept in mind that all need to be contextualized within the specific SES in which they are deployed (see Figure 6.1).

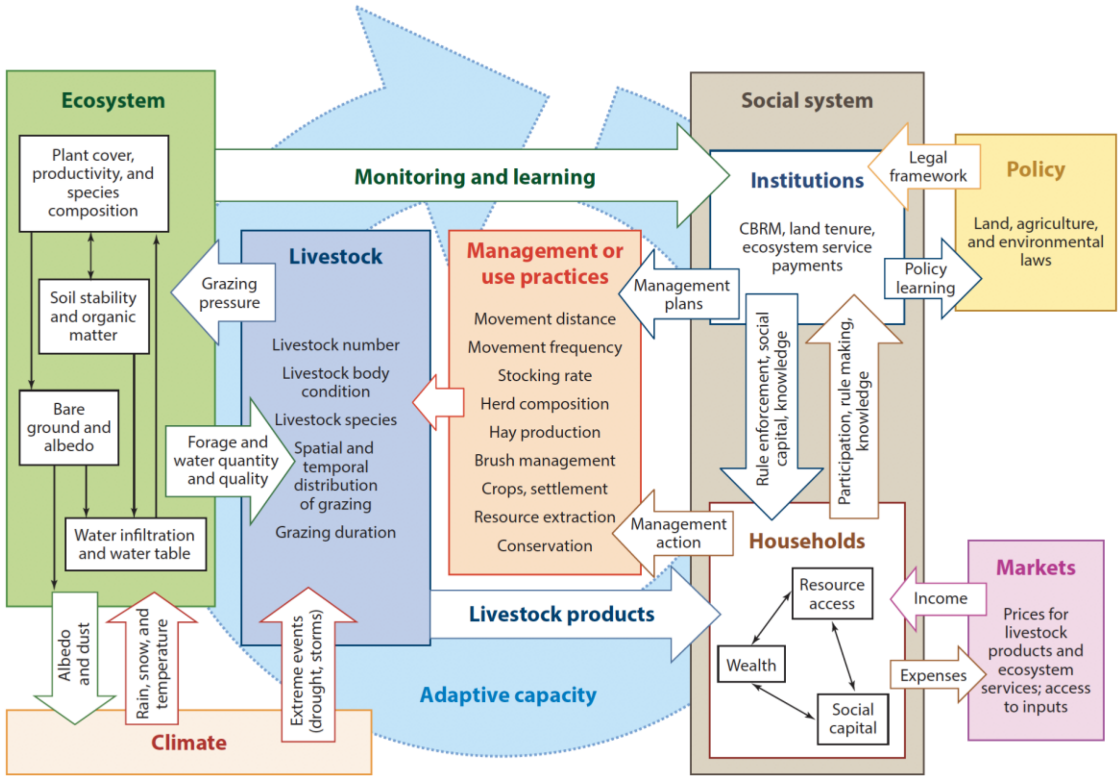


Figure 1

Model of a rangeland social-ecological system (23). Abbreviation: CBRM, community-based rangeland management.

Figure 6.1 Example of a socio-ecological system (in this case, a rangeland). Source: Reid et al. 2014

Recognition of the importance of SESs is at the heart of moves towards interdisciplinary landscape approaches in policy and governance (Rawlins et al.,2013) and can help address questions of how to ‘scale up’ multifaceted responses that target a variety of impacts leading towards more resilient management (Walker et al.,2006; Bestelmeyer et al.,2012). Framing response options within SESs also recognises the interactions *between* different response options (e.g., securing land tenure can improve outcomes for forest restoration) (Chirwa and Mahamane 2017). Numerous theoretical models have been proposed for analysing components of SESs (Binder et al.,2013); a few characteristic examples include ecosystem services frameworks (Díaz et al.,2015; Reed et al.,2015; Tallis et al. 2018) , the Sustainable Livelihood Approach (Scoones 1998), and the Driver, Pressure, State, Impact, Response (DPSIR) approach (Rawlins et al.,2010; Carr et al. 2007).

6.2.2.1 Contested understandings of problems and uneven vulnerabilities

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). Biophysical changes like land degradation or climate variability are always influenced and mediated through social, cultural and political factors, often with a lack of agreement on causality (Blaikie 2016; Blaikie et al.,1987; Ribot 2014). Drivers of environmental change usually have primarily social or economic rather than technological roots, which requires acknowledgement that response options that do not aim at reducing the drivers of change may thus be less successful (Schwilch et al.,2014)

Response options also must take into account that the impacts of both environmental change and intervention responses are distributed unevenly among populations. Understanding the integrative response options available and appropriate in a given context requires an understanding of the specificities of social vulnerability in particular. 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 like 'no-brainers' to implement (Mutoko et al.,2014; (Cavanagh et al.,2017). Thus, assessment of the differentiated vulnerabilities that may prevent response option adoption needs to be considered as part of any package of interventions.

Further, while environmental changes like land degradation have obvious social and cultural impacts, as discussed in the preceding chapters, so too do response options, and thus careful choices must be made 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, approprite 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 stakeholders who are the objects of interventions, given the contexts of the SES in which the response option will be implemented.

6.2.2.2 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 appropriate knowledge production, attention to gender issues, and aspects of better governance, including social capital factors and institutional facilitation. These enabling conditions 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. We note some of the more important enabling conditions below and how they can work together with individual response options to produce more sustainable outcomes. Chapter 7 then zooms out to a wider lens 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 these contexts within which response options will be delivered.

Knowledge production: Lack of connection between science and practice has hampered adoption of many response options; simply presenting ‘scientifically’ derived response options is not enough (Marques et al. 2016). Knowledge exchange, social learning, and other concepts are increasingly being incorporated into understandings of how to facilitate sustainable land management (Djenontin et al.,2018), as evidence suggests that negotiating the complexity of SESs requires flexible learning arrangements in particular (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). 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 based on these 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).

As part of knowledge co-production, the importance of recognising and incorporating local knowledge (LK) and indigenous knowledge (IK) is also emphasised. Local practices of water management, soil fertility management, improved grazing, restoration and sustainable management of forests are often well-aligned with response options generated by scientists (Marques et al. 2016). However, these often reliable sources of information are unfortunately generally overlooked by formal systems of decision-making, despite the fact that much of the literature encourages an integration of both scientific and indigenous knowledge where possible (Green and Raygorodetsky 2010; Speranza et al. 2010). IK is particularly useful in characterising conditions of SESs where formal data collection may be sparse (Schick et al. 2018), and can contribute to accurate predictions of impending environmental change (Green and Raygorodetsky 2010 ; Orlove et al. 2010). LK and IK often plays an important role in facilitating climate adaptation in particular (Adriansen et al.,2002; Leon et al. 2015). Further, many indigenous peoples (IPs) have specific historical and cultural connections to land that are not easily understood or captured in quantitative indicators such as economic production or land use. The specific vulnerabilities of IPs in the context of climate change additionally needs to be part of the considerations in choosing response options, including cultural changes, population, and mobility changes (Rigby et al. 2011).

Gender dynamics: Gender structures vulnerability and access to resources and influences how response options should be implemented. Gender inequality also 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 to their local areas under climate change (Nelson et al. 2002). Response options also have potential gender impacts; for example, securing land tenure can potentially have positive gender impacts in giving women empowerment over decision-making in agriculture (Fonjong et al. 2016), while in another case securing land tenure for carbon sequestration projects has reduced women’s access to mangroves in West Africa by shifting control to men and the state (Cormier-Salem 2017). Every response option considered in this chapter potentially has a gender dimension to it that needs to be taken into consideration; for example, to address food security through sustainable intensification will clearly have to address women farmers in Africa (Kondylis et al.,2016) (Garcia et al.,2017) (For further information, see Cross-Chapter Box 6: Gender, Chapter 7).

Social capital and collective action: Research that shows that people willingly come together to help 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 can 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). (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 benefit; the presence of leadership; presence of social capital and trust; and autonomy and independence to make and enforce rules. Presence of social capital is considered as one of the most significant factors that initiate and support collective (Adger 2009). Social capital is based on trust, reputation, and reciprocal action. Having social capital facilitates the development of common rules and norms, as well as punishments and sanctions, which are mutually agreed upon and which will ensure group interests and action are supported by individuals (Pretty 2003). 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.,(2003) lay out important policy directions for facilitating collective action. These include: providing information; dealing with conflict; inducing rule compliance; providing physical, technical or institutional infrastructure; and being prepared for change.

Collective action is important because 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 early warning systems. Many of these could be understood as community-based adaptation (CBA) strategies, as grounding responses 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), generally through participatory processes, such as 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). Yet participatory protocols are not enough if frameworks for social trust do not exist (Bautista et al.,2017), and if structured processes to select response options together with stakeholders (Franks 2010; Schwilch et al.,2012), are not in place. Evaluations of community-based response options have been generally positive ((Karim and Thiel 2017). Yet wider adoption of community-based approaches is potentially hampered by several factors: 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).

Importance of governance frameworks: Studies have noted that while adaption of response options by individuals may depend on individual assets and motivation, larger structural and institutional factors are almost always equally if not more important (Adimassu et al.,2016; Djenontin et al.,2018), though harder to capture in research variables (Schwilch et al. 2014a). Governance frameworks 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. Institutional governance provides a framework for understanding how useful local and national policy has been in creating an enabling environment for SLM practices, for example (Adimassu et al. 2013). Many of Ostrom's design principles for governance can be applied to response options in areas such as SLM: (1) clearly defined boundaries; (2) proportional equivalence between benefits and costs; (3) collective choice arrangements; (4) monitoring; (5) graduated sanctions; (6) conflict-resolution mechanisms; (7) minimal recognition of rights to organise; and (8) nested enterprises (Ostrom 1990; Huntjens et al. 2012; Davies 2016) Unfortunately, studies of many natural resources and land management policy systems in developing countries in particular show the opposite in institutional frameworks: a lack of flexibility, strong hierarchical tendencies, and a lack of local participation (Ampaire et al. 2017).

It is simply not a matter of putting the 'right' institutions in place, however, as these governance principles 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 impact on the ability to implement different response options. For example, land grabbing as a driver of exclusion and poverty is a factor of the unequal power dynamics between large agribusiness concerns and local farmers, which may be hard to reverse in certain governance situations of unequal distributions of power (Verma 2014). The inability of many national governments to address social exclusion in general will have impacts on 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 REDD projects run the risk of reversing trends towards decentralisation in forest management and create new power disparities between the state and local actors (Phelps et al.,2010).

6.2.3 Challenges and response options in current and historical interventions

Multiple interlinkages between land degradation, desertification, food security, biodiversity and climate change have been reported in previous chapters, with focus on biophysical land-climate interactions (Chapter 2) and on impacts and responses of desertification (Chapter 3), land degradation (Chapter 4) and food security (Chapter 5), respectively. Here, we provide historical and current examples of such interlinkages between challenges and of land-based response options in human-dominated and 'wildland' ecosystems.

There is an extensive and globally-relevant scientific literature on the historical and current role of specific land-based mitigation options (see Chapter 2; Smith et al. 2014), including forest management and restoration (Canadell and Raupach 2008; Stanturf et al. 2014) agriculture soils and livestock management (FAO 2010; Paustian et al. 2016), agro-forestry systems (Ramachandran Nair et al. 2010a) and the restoration of wetlands and peatlands (Leifeld and Menichetti 2018).

By contrast, until recently relatively fewer studies assessed - mostly at regional level – the interlinkages between options, for example, on the role of agriculture intensification for reducing deforestation (Lapola et al. 2014), or between challenges, for example, between mitigation and adaptation (Locatelli 2011). The reason is that analysing the co-benefits, adverse-effects and trade-offs of land-based response options is challenging for a number of reasons (Bustamante et al. 2014). First, the effects of each option depend on the context and the scale of the intervention, that is the effects are site-specific, and generalisations are difficult. Second, potential responses do not necessarily overlap geographically, socially or temporally. Third, there is no agreement on how to attribute co-benefits and adverse-effects to specific mitigation measures; and fourth there are no standardised metrics for quantifying many of these effects. However, an increasing numbers of tools are available allowing integrated assessment of multiple outcomes for different challenges (e.g., Vogt et al. 2011; Townsend et al. 2012; Smith et al. 2013; Turner et al. 2016), and national level approaches to define land sector sustainability have been proposed (Gao and Bryan 2017a). This is reflected also in the rapidly increasing interest in global-level integrated approaches, taking into account the sustainable development (e.g., Dooley and Kartha 2018), planetary boundaries (Heck et al. 2018) and with a focus on nature-based solutions (Griscom et al. 2017a; Nesshöver et al. 2017).

The human domination of ecosystems has resulted in the development of anthropogenic biomes (or anthromes). Ellis and Ramankutty (2008) identified six major anthrome types through empirical analysis of global population, land use, and land cover: dense settlements, villages, croplands, rangelands, forested and wildlands (without evidence of human occupation or land use, about 22% of Earth's ice-free land) (Figure 6.2). Agricultural land-based response options (see 6.4.2 and 6.5.2) tend to dominate in the croplands and rangelands anthromes, forestry responses (see 6.4.1 and 6.5.1) in the forested anthromes and ecosystem based adaptation (see 6.5.4) responses in the wildland anthromes. Specific village and dense settlements land-based response options were also documented in the literature (e.g. Ahrends et al. 2010; Huber-Sannwald et al. 2012; Hassan and Nazem 2016).

Anthromes are exposed to multiple challenges, including land degradation, climate change, food insecurity, water stress and threatened biodiversity. The spatial distribution of individual land challenges is shown in Figure 6.2, based on recent studies:

- As an indicator of recent land degradation, an estimate is made from long-term (1982–2006) NDVI decline, by correcting for rainfall and afforestation and by masking areas with saturated NDVI (Le et al., 2016);
- Magnitudes of change in local climates between 2000 and 2070 is estimated following the dissimilarity index calculated by (Netzel and Stepinski 2018), contrasting slow (dissimilarity index below 0.7) and rapid (index equal to 0.7 or above) climate change;
- While recognising that food security consists of more than undernourishment (Chapter 5), prevalence of chronic undernourishment (higher or equal to 5%) by country in 2015 (FAO 2017) is presented as an indicator of food insecurity;
- While recognising that biodiversity concerns more than only threatened endemic species, as an indicator of biodiversity, threatened terrestrial biodiversity hotspots (areas where exceptional concentrations of endemic species are undergoing exceptional loss of habitat) are used as an indicator of biodiversity (Myers et al.,2008);
- Groundwater stress is estimated for ratios of groundwater abstraction over recharge above one and is mapped for the Cropland and Village anthromes, which abstract water for irrigation (Gassert et al.,2017);

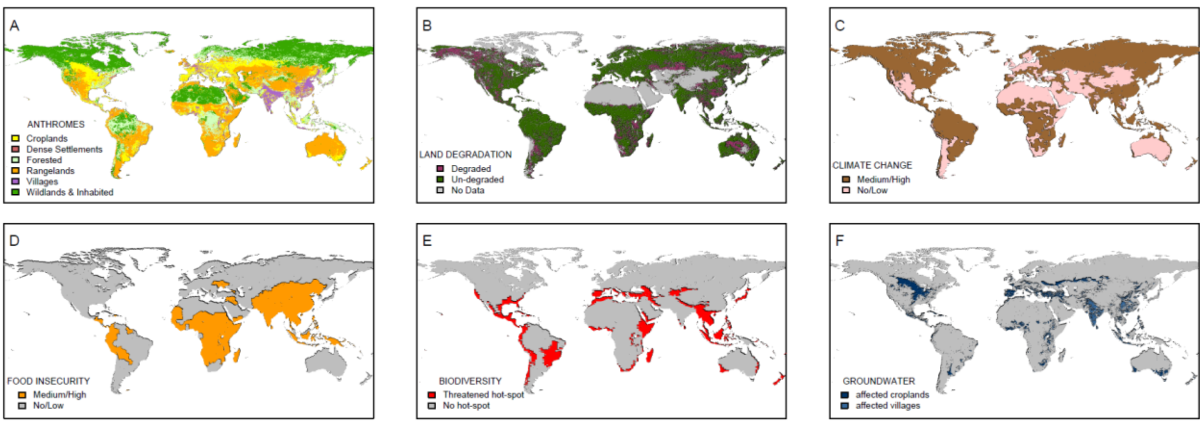


Figure 6.2 Global maps of (A) anthropogenic biomes (or anthromes, after Ellis and Ramankutty 2008): dense settlements, villages, croplands, rangelands, forested (semi-natural forests) and wildland and

inhabited lands (including primary forests and barren); B land degradation (Le et al. 2016); C climate change (Netzel and Stepinski 2018) ; D, food insecurity (FAO 2017); E, threatened biodiversity hotspots F, groundwater stress affecting cropland and village anthromes (Gassert et al.,2015). For definitions, see text

Table 6.1 Anthrome area (% ice-free land) and anthrome percentage exposure to individual challenges (see text for definitions)

Anthrome[1]	**Anthrome area**	**Rapid climate change[2]**	**Land degradation[3]**	**Food insecurity[4]**	**Threatened biodiversity hotspot[5]**	**Ground water overuse[6] (croplands & villages)**
	% of ice-free land area [1]		*% anthrome area exposed to an individual challenge*			
Dense settlement	1.2	75.0	17.5	30.0	31.9	-
Village	5.4	69.9	24.0	76.5	28.2	66.1
Cropland	14.7	71.1	21.8	27.2	27.1	61.6
Rangeland	26.8	45.0	23.8	42.6	20.4	-
Forested (semi-natural)	14.0	91.1	17.5	36.6	20.6	-
Wild & Inhabited	38.0	77.3	17.2	12.5	2.6	-
All anthromes	100.0	69.3	20.0	29.7	15.2	61.7

(1) Ellis and Ramankutty (2008); (2) (Netzel and Stepinski 2018)**; (3)** (Le et al. 2016)**; (4)** (FAO 2017) **(% prevalence of undernourishment by country in 2015); after** (Myers et al.,2008)**; (6)** (Gassert et al.,2015)**.**

Anthromes occupy contrasted shares of the ice-free land area, with dense settlements and villages concentrating the majority of the global population in less than 7% of the area, while semi-natural forests, wildland and inhabited anthromes occupy more than half of the ice-free land area on a global scale (Table 6.1). Rapid climate change affects close to 70% of the ice-free land area, while the land degradation and food insecurity challenges are concentrated in about 20% and 30% of global land, respectively. All anthromes host threatened biodiversity hotspots. Irrigation potential is constrained by groundwater overuse in more than 60% of the Cropland and Village anthromes and the latter are strongly exposed to food insecurity (Table 6.1).

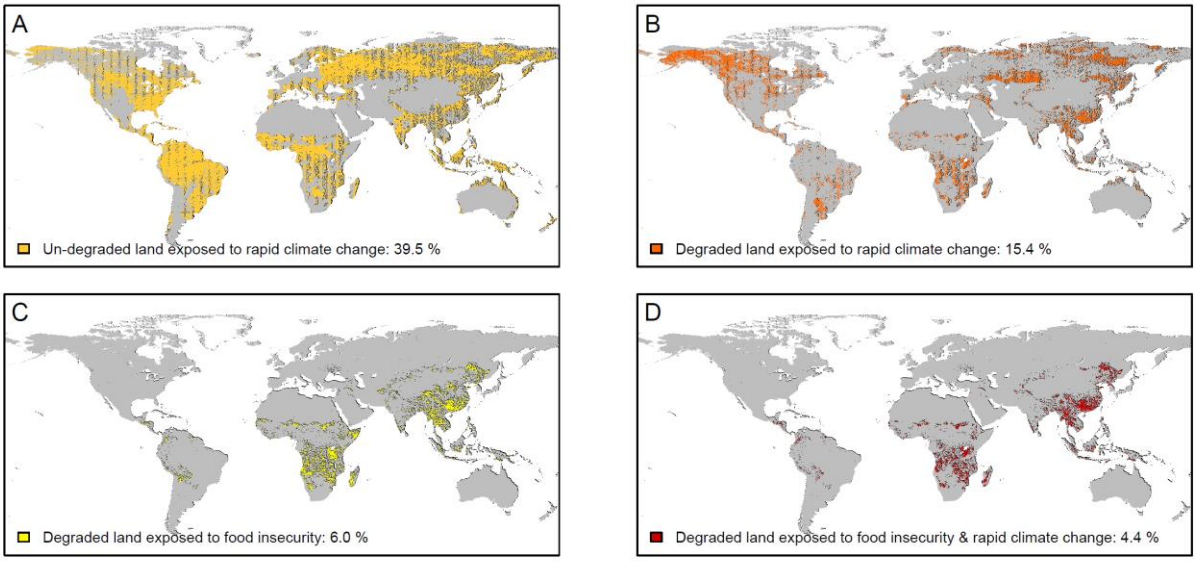


Figure 6.3 Spatial distribution of exposure to selected multiple land challenges. A. Un-degraded land exposed to rapid climate change; B. Degraded land exposed to rapid climate change; C. Degraded land exposed to food insecurity; D. Degraded land exposed to rapid climate change and food insecurity (for definitions, see text; references as in Figure 6.2)

Approximately 15% of the global ice-free land area is exposed to a combination of land degradation and rapid climate change, while the combination of the land degradation and food insecurity challenges is predominantly observed in sub-Saharan Africa and in South Asia. Globally, 4.4% of the ice-free land area is exposed to a combination of land degradation, rapid climate change and food insecurity with largest areas also in sub-Saharan Africa and South Asia (Figure 6.).

Anthromes used for agriculture show contrasted regional distributions of the combined land degradation, rapid climate change and food insecurity challenges (Figure 6.4), with largest affected areas located in South and East Asia for the Village anthrome, in Sub-Saharan Africa, East Asia and Latin America for the Rangeland anthrome and for the Cropland anthrome areas affected in multiple regions including Asia, sub-Saharan Africa and central America. Anthromes not used for agriculture also show contrasted distributions of areas exposed to combinations of rapid climate change, land degradation and threatened biodiversity hotspots with the largest area in South-East Asia for the semi-natural forests anthrome, while scattered and relatively small areas are exposed to a combination of these challenges in the Wildland and Inhabited anthromes (Figure 6.4).

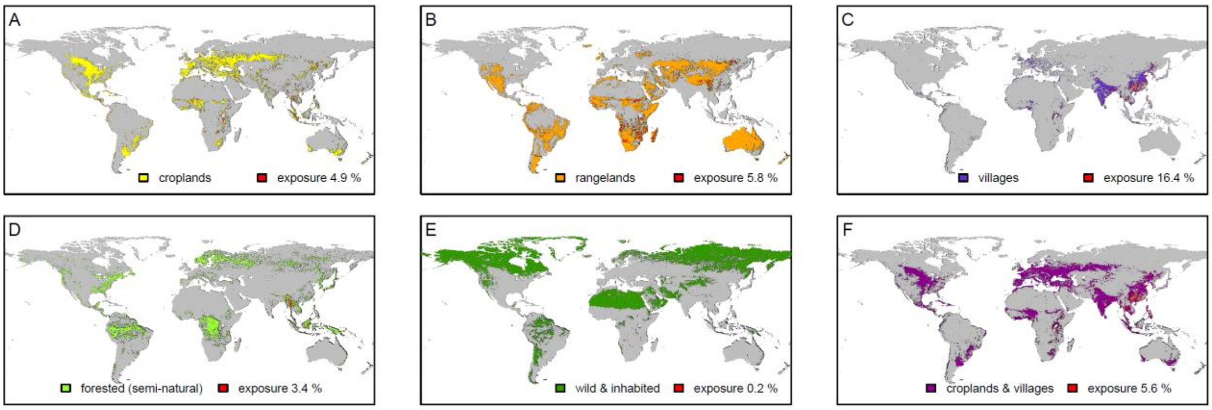


Figure 6.4 Spatial distribution of exposure to selected multiple challenges by anthrome. A, B, C. Cropland, Village and Rangeland anthromes and their exposure to land degradation, rapid climate change and food insecurity. In (F), exposure to groundwater stress, rapid climate change, land degradation and food insecurity is mapped for both Cropland and Village anthromes. Semi-natural Forests (D) and Wildland and Inhabited (E) anthromes and their exposure to land degradation and rapid climate change in areas with threatened biodiversity hotspots. In red, anthrome area exposed to the selected multiple challenges. In grey, areas not covered by the anthrome

The global land distribution by anthrome and by number of local land-based challenges (Figure 6.5) shows less frequent exposure to multiple challenges in the Wildland & Inhabited anthrome compared to Semi-Natural forests and Rangelands anthromes (often exposed to one challenge or more), to Croplands and Dense Settlements anthromes (often exposed to two challenges or more) and to the Villages anthrome (often exposed to three challenges or more). Therefore, there is a general trend of increased exposure to multiple land challenges in anthromes which are used more intensively.

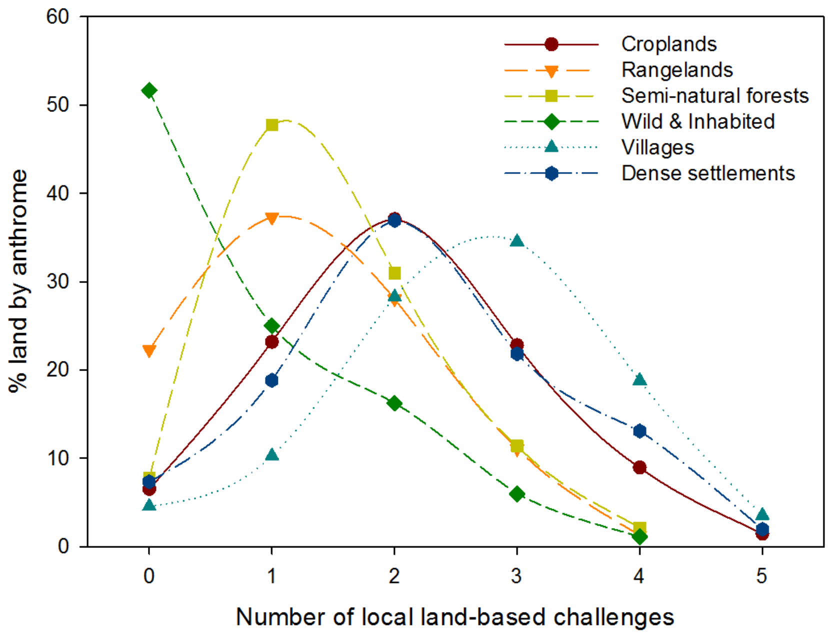


Figure 6.5 Percentage distribution of land area by anthrome and by number of local land-based challenges including: i) land degradation (and desertification in drylands), ii) rapid climate change, iii) food insecurity, iv) threatened biodiversity hot-spot, v) depleted groundwater resources (in anthromes abstracting water: croplands, villages and dense settlements)

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: A to F). Taken together, these case studies illustrate the large contrast across anthromes in land-based interventions and 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 still 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 in these highlands, with approximately 90% of the households depending 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 ca. 2000, the large-scale implementation of Soil and Water Conservation (SWC) measures, integrated catchment management, conservation agriculture and indigenous tree regeneration 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 provide labour for SWC during January as 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 are 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 the land restoration measures (Gebremeskel et al. 2018).

B. Rangelands. Biodiversity hotspot, land degradation and rapid 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). It has undergone extensive cattle ranching (limited mechanisation, low use of fertiliser and seed inputs) through 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 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 increases soil organic carbon and reduces 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, which has already been significantly reduced (−82% emissions from deforestation over 2004–2014 in the national inventory), and increased pasture intensification, provide the basis for an 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).

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

During the last two decades, forest cover in Indonesia reduced by 11.5 Mha in the period 1990-2000 (Stibig et al. 2014), and of approximately 15.8 Mha in the period 2000–2012 (Hansen et al. 2013a), mainly due to the conversion of tropical forests into agricultural lands (e.g., oil palm, pulpwood plantations). According to the most recent estimates, deforestation in Indonesia mainly concerns primary, intact, and degraded forests, thus strongly contributing to biodiversity loss, and to the reduction of carbon sequestration potentials (e.g., Margono et al. 2014). For example, Graham et al. (2017) estimated that the following strategies to reduce deforestation and degradation may cost-effectively increase carbon sequestration and reduce carbon emissions in 30 years: reforestation (965 MtC), limiting the expansion of oil palm and timber plantations into forest (836 MtC and 831 MtC, respectively), reducing illegal logging (638 MtC), and halting illegal forest loss in Protected Areas (414 MtC); at a total cost of USD 15.7 tC^{-1}. The important role of forest mitigation in Indonesia is confirmed by the Nationally Determined Contribution, where between half and two-thirds of the 2030 emission target relative to business-as-usual scenario is expected to derive from reducing deforestation, forest degradation, peatland drainage and fires (Grassi et al. 2017b). In particular, avoiding deforestation and reforestation have multiple co-benefits with adaptation by improving biodiversity conservation, and employment opportunities, while reducing illegal logging in protected areas, while providing multiple co-benefits can have adverse side-effects since they may deprive local communities' access to natural resources (cf. Graham et al. 2017). On the adaptation side, the adoption of the Roundtable on Sustainable Palm Oil (RSPO) certification in oil palm plantations reduced deforestation rates of 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, considering that oil palm plantations are one of the most impacting driving forces of deforestation in Indonesia (e.g., exacerbated in Borneo), it is argued that RSPO still lacks information about land-clearing trajectories and of comprehensive assessments (Gaveau et al. 2016). About adaptation options, the community forestry scheme "Hutan Desa" (Village Forest) in Sumatra and Kalimantan was estimated to contribute to avoid deforestation (co-benefits with mitigation: between 0.6 and 0.9 ha km^{-2} in Sumatra, and between 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 Nature's Contributions to People provision) (e.g., Pohnan et al. 2015). Finally, the establishment of Ecosystem Restoration Concessions in Indonesia (more than 0.55 Mha of forests now covered, and 1.6 Mha allocated to 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 if compared with timber concessions (Silalahi et al. 2017).

D. Wildland anthrome. Biodiversity hotspot, land degradation and rapid climate change: rewilding and managing abandoned agricultural land in Mediterranean Europe

Since the 1950s, farmland abandonment has been occurring primarily in developed countries, in Europe, North America and Oceania, but also in some developing and transition economy countries such as China, mainly as a result of a decline in the agricultural labour and of changing socio-economic factors causing small scale farmers to move to cities (Li and Li 2017). Much of the abandoned agricultural land is likely to display altered soil quality, a depleted native biota with established alien species and poor ecosystem connectivity. Land-use policies in abandoned agricultural landscapes can differ across regions with a dominant focus on pre- or post-abandonment conservation (Queiroz et al. 2014). Since the 1990s Europe has experienced a drastic reduction in agricultural land area and most studies have focused on the conservation of the pre-abandonment status, reporting dominantly negative impacts of agricultural abandonment for biodiversity and Nature's Contributions to People (Queiroz et al. 2014). Under wet Mediterranean climate conditions, a catchment in the west of Slovenia re-wilded about 70% of the area over a period of 30–50 years, leading to soil improvements (soil organic matter content, bulk density and aggregate stability, van Hall et al. 2017), as well as landscape benefits (reduction of flood risks and runoff discharge). However, the increase in forest cover reduced the stream flow in summer showing that Nature's Contributions to People may decline under extensive rewilding (Keesstra et al. 2018). When the whole catchment area is not forested, but areas with low erosion risks are transformed in extensively managed grasslands or in mixed systems combining trees and grasses as in agroforestry, multiple benefits for water resource management, biodiversity (especially endangered bird species from grassland areas) and tourism can be realised (Keesstra et al. 2018). Another example is provided by the traditional agroforestry system in southwestern Iberian peninsula (Dehesa) combining extensive pastures and indigenous evergreen oak trees. Land abandonment combined with increased droughts and fires have induced loss of productivity and of tree health (Godinho et al. 2016). Nature based solutions adopted in this context include the use of biodiverse pastures rich in nitrogen-fixing legume species which provide soil cover during the year and tend to increase soil organic matter through enhanced plant productivity (Keesstra et al. 2018). Scenarios show that increasing the nature-based use of farmland, forests, and urban areas could create additional jobs in Europe and increase total socioeconomic benefits of Nature's Contributions to People (Maes and Jacobs 2017).

E. Villages. Land degradation, groundwater overuse, rapid climate change and food insecurity: climate smart villages in southern India

Indian agriculture, with 80% of farmers being smallholders (less than 0.5 ha), which combines monsoon-dependent rainfed (58%) and irrigated agriculture, is exposed to climatic variability and climate change. Over the past years, the frequency of droughts, cyclones, and hailstorms increased, with 2002, 2004, 2009, 2012, and 2014 being severe droughts (Rao et al. 2016), as well as 2016–2017, with large negative yield impacts for major crops like wheat (Zhang et al. 2017). The development of submersible pump technology in the 1990s resulted in a dramatic increase of the irrigated agricultural area, which has been supported by public policies that provide farmers free electricity for groundwater irrigation (Shah et al. 2012). This shift caused agricultural practices to depend heavily on irrigation from groundwater and induced a groundwater crisis, with large impacts on socio-ecosystems. An increasing number of farmers report borewell failures for two main reasons: borewells have run dry after excessive pumping, or no water was found in newly drilled borewells. The decrease in groundwater table level suppressed the recharge of river beds, turning main 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 are declining soil organic matter and fertility under monocultures and rice/wheat systems. Land is scarce, meaning that the potential for expanding the farmed area is very limited (Aggarwal et al. 2018). In rural areas, diets were deficient in protein, dietary fiber and iron and revolved around the cereals and pulses grown and/or procured through the welfare programs (Vatsala et al. 2017). Cultivators are often indebted and suicide rates among them 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 capacity and interest of the farmers and of the local government (Aggarwal et al. 2018). The selected interventions included crop diversification, conservation agriculture (minimum tillage, residue retention, laser levelling), improved varieties, weather-based insurance, and agro-advisory services, precision agriculture and agroforestry. Farmers' cooperatives were set up for custom hiring farm machinery, securing government credit for inputs, and sharing of experiences and knowledge. Tillage practices and residue incorporation increased rice–wheat yields by 5–37% and income by 28–40% and reduced GHG emissions by 16–25%. Water-use efficiency also increased by 30% (Jat et al.,2014). The resultant portfolio of options proposed by the CSV approach has been integrated with the agricultural development strategy of some states like Haryana.

F. Dense settlements. Rapid climate change, land degradation and groundwater stress: urban farming and green infrastructures in USA

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 mortality rates increasing by 30–130% in major cities from developed countries (Norton et al. 2015). There is evidence that 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 infrastructures in cities. Urban green infrastructure can be defined as public and private green spaces, including 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 and surface temperature maxima and variation and avoid urban heat. During an extreme heat event in Melbourne, Australia, a 10% increase in vegetation cover was estimated to reduce daytime urban surface temperatures by approximately 1°C (Coutts and Harris 2013). Urban farming, is one component of urban green infrastructures which is largely driven by the desire to reconnect food production and consumption (Thomaier et al. 2015). Even though urban farming can only meet a very small share of the overall urban food demand, it can add to the supply of fresh and local food—especially perishable fruits and crops that usually travel a long way into cities and are sold at high prices. Ground-based urban farming dominates urban food production, but faces growing land availability and soil quality constraints. Food-producing urban gardens and farms are often started by grassroots initiatives that occupy vacant urban spaces, creatively transforming them often. 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 N. America in cities such as New York City, Chicago and Toronto (Thomaier et al. 2015), where they depend on the availability of vacant buildings and roof tops thereby competing with other types of use, such as roof-based solar systems. One critical aspect of urban farming is the potentially high level of soil pollution and of air pollutants in urban settings, which may lead to crop contamination and health risks that could be reduced in controlled environments. Comprehensive assessments of the potential of urban green infrastructures and urban farming for improving diets and health in cities exposed to climate change and rising food demand are however still lacking.

6.2.4 Challenges represented in future scenarios

The previous section provided an assessment of five land challenges (climate change, land degradation, food insecurity, threatened biodiversity hotspots, and groundwater stress) today. In this section, we assess the evolution of these five challenges in the future, focusing on global scenarios without explicit response options. The effect of response options on these land challenges in the future is discussed in Section 6.5.4.

Climate change: Absent any 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. 2014a;). The level of warming varies depending on the climate model (Collins et al. 2013), uncertainties in the Earth system (Clarke et al. 2014a), and socioeconomic/technological assumptions (Clarke et al. 2014a; Riahi et al. 2017) In the RCP8.5, warming over land is higher by 1°C on average than global mean temperature rise; warming in the arctic region is about 5°C larger 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).

Land degradation: Changes in temperature and precipitation have implications for land degradation. For example, dryland area is expected to increase by 23% in the RCP8.5 (Huang et al. 2016) due to climate change. Human influences on land degradation (see Chapter 4) were not assessed in the scenarios included here.

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. 2015; Ringler et al. 2016; Baldos and Hertel 2015) and 0–600 million in 2100 (Hasegawa et al. 2015b). Food prices in 2100 in non-mitigation scenarios range from 0.9 to about 2 times their 2005 values (Hasegawa et al. 2015b; Calvin et al. 2014a; Popp et al. 2017). Higher income (e.g., SSP1, SSP5), higher yields (e.g., SSP1, SSP5), and less meat intensive diets (e.g., SSP1) tend to lead to reduced food insecurity.

Biodiversity: Future species extinction rates vary from modest declines to 100-fold increases from 20th century rates, depending on the species, the degree of land-use change, and the level of climate change. (Pereira et al.,2010).Mean species abundance (MSA) is also estimated to decline in the future by 10–20% in 2050 (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 both water supply and water demand 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; Kim et al. 2016 ;Bonsch et al.,2015)Wada and Bierkens 2014; Graham et al. 2018; Hejazi et al. 2014) total water withdrawals at the end of the century range from 5000 to 13000 $km^3\ yr^{-1}$ (Wada and Bierkens 2014a; Hejazi et al. 2014a; Graham et al. 2018; Kim et al. 2016). The magnitude of change in both irrigation and total water withdrawals depend on population, income, and technology (Hejazi et al. 2014a; Graham et al. 2018a). The combined effect of changes in water supply and water demand will lead to an increase of between 1 and 6 billion people living in water stressed areas (Schlosser et al. 2014; Hanasaki et al. 2013a; Hejazi et al. 2014c).

Scenarios with Multiple Challenges: Many of the studies quantifying the future evolution of these five land challenges used the Shared Socioeconomic Pathways (SSPs;) (O'Neill et al. 2014) as an underlying framework. These studies can be used to assess which future pathways could experience multiple challenges in the future. The SSP3 (Fujimori et al.,2017) is a scenario with high challenges to mitigation and high challenges to adaptation. The resulting scenario includes:

- Continued *climate change*: radiative forcing exceeds 7 W m^{-2} in 2100 (Fujimori et al.,2017).
- High levels of *food insecurity*: about 600 million malnourished in 2100 (Hasegawa et al. 2015b),
- Declines in *biodiversity*: mean species abundance increase from 34% in 2010 to 46% in 2100 (UNCCD 2017), and
- High *water stress*: about 5.5 billion people live in water stressed areas in 2100 (Hanasaki et al. 2013).
- The SSP4 (Calvin et al. 2017) is a scenario with high challenges to adaptation but low challenges to mitigation. The resulting scenario includes:
- Continued *climate change*: global mean temperature increases by 3.7°C in 2100 (Calvin et al. 2017).
- High levels of *food insecurity*: about 400 million malnourished in 2100 (Hasegawa et al. 2015b), and
- High *water stress*: about 3.5 billion people live in water stressed areas in 2100 (Hanasaki et al. 2013).

Biodiversity loss was not quantified for the SSP4. All other SSPs have continued *climate change* and high *water stress* (Hanasaki et al. 2013) but *food insecurity* declines substantially in the future due to increased income (Hasegawa et al. 2015b).

6.3 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 a) land management, b) value chain management and c) risk management (Table 6.2). Note that the integrative response options are not mutually exclusive (e.g., cropland management might also increase soil organic matter stocks), and a number of the integrated response option are comprised of a number of practices (e.g., improved cropland management is a collection of practices consisting of a) management of the crop: including high input carbon practices, e. g., improved crop varieties, crop rotation, use of cover crops, perennial cropping systems, agricultural biotechnology, b) nutrient management: including optimised fertiliser application rate, fertiliser type [organic and mineral], timing, precision application, 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). Note that enabling conditions such as indigenous and local knowledge, gender issues, governance etc. are not categorised as integrative response options (see Section 6.2.2). Some suggested methods to address land challenges are better described as *overarching goals* than as response options. For example, the *conservation of biodiversity* is the very broad goal of other response options, including for example, reduced deforestation (6.3.1.15), peatland restoration (6.3.1.21), coastal wetland restoration (6.3.1.19), ecosystem-based adaptation (6.3.1.14), management of pollution (6.3.1.16), management of invasive species (6.3.1.17) and various forms of sustainable land management that include increasing productivity (6.3.1.5) and sustainable forest management (6.3.1.7), some of which might also reduce habitat fragmentation. Other suggested methods to address land challenges are better described as *overarching frameworks* than as response options. For example, *climate smart agriculture* is a collection of response options aimed at delivering mitigation and adaptation in agriculture, including improved cropland management, grazing land management and livestock management (6.3.1.2, 6.3.1.3 and 6.3.1.4). Additionally, policy goals can be considered overarching targets, such as *land degradation neutrality* (discussed further in Chapter 7). For this reason, broad goals such as *conservation of biodiversity* or *land degradation neutrality*, and overarching frameworks, such as *climate smart agriculture* do not appear as response options in the following sections, but the component integrative response options that contribute to the goals or over-arching frameworks do appear.

Table 6.2 Integrated response options available to address the land challenges of climate change mitigation, climate change adaptation, desertification, land degradation and food security, categorised by those that rely on land management, value chain management and risk management. The crosses mark the main indicative use of the integrated response options. For further interactions across the land challenges, see Section 6.5

Category	Integrative response option	Climate mitigation Ch2	Climate adaptation Ch2	Desertification Ch3	Land Degradation Ch4	Food security Ch5
Response options based on land management	Increased soil organic matter content (and reduced losses)	X	X	X	X	X
	Improved cropland management	X	X	X	X	X
	Improved livestock management	X	X	X	X	X
	Improved grazing land management	X	X	X	X	X
	Increased food productivity	X	X	X	X	X
	Agro-forestry	X	X	X	X	
	Sustainable forest management	X	X	X	X	
	Agricultural diversification		X	X	X	X
	Management of erosion	X	X	X	X	X
	Prevent / reverse soil salinization			X	X	X
	Prevention of compaction			X	X	X
	Fire management	X	X	X	X	
	Management of landslides and natural hazards			X	X	
	Ecosystem-based adaptation	X	X	X	X	X
	Reduced deforestation and degradation	X	X	X	X	
	Management of pollution including acidification			X	X	X
	Management of invasive species / encroachment		X	X	X	X
	Reforestation	X	X	X	X	
	Restoration and avoided conversion of coastal wetlands	X	X	X	X	
	Biochar	X	X	X	X	
	Restoration and avoided conversion of peatlands	X	X		X	
	Afforestation	X	X	X	X	
	Avoidance of conversion of grassland to cropland	X		X	X	
	Enhanced weathering of minerals	X				
	Bioenergy and BECCS	X				
Response options based on value chain management	Dietary change	X	X	X	X	X
	Reduce post-harvest losses	X	X	X	X	X
	Reduce food waste (consumer or retailer)	X	X	X	X	X
	Promotion of value-added products					X
	Stability of food supply		X			X
	Improved food transport and distribution	X	X			X
	Urban food systems		X			X
	Improved efficiency and sustainability of food processing, retail and agri-food industries	X	X			X
	Increased energy efficiency in agriculture	X	X			X
	Material substitution	X	X			
Response options based on governance and risk management	Land tenure / ownership		X	X	X	X
	Prevention of land grabbing		X	X	X	X
	Management of urban sprawl		X	X	X	X
	Livelihood diversification		X			X
	Promotion of seed sovereignty		X			X
	Early warning systems for disaster risk reduction		X			X
	Commercial crop insurance		X			X

In the sections below, we describe the characteristics of the integrated response options, and describe their impacts on each of mitigation, adaptation, desertification, land degradation and food security.

6.3.1 Integrated response options based on land management

6.3.1.1 Increased soil organic matter content (and reduced losses)

Increased soil organic matter content (and reduced losses) can be achieved across a range of different land uses, including cropland, grazing land, peatlands/wetlands and forestry – and can be promoted by improved cropland, grazing land and forest management, by addition of biochar, as well as through afforestation / reforestation in most circumstances (Smith 2013) – see also sections on these response options in this section). 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 (Smith et al. 2014b; Smith 2016a).

Soil organic matter management increases soil carbon stocks, thereby removing CO_2 from the atmosphere so has been proposed as a mitigation option (Paustian et al.,2016). In addition, increasing soil organic matter content has been shown to increase the water holding capacity of the soil (Keesstra et al.,2016; Lal 2016), thereby conferring resilience to climate change and enhancing adaptation capacity (Lal 2016). Soil management options that increase organic matter content are proposed as measures to address both desertification (Bestelmeyer et al. 2015) and land degradation (FAO et al. 2015). There is some evidence that crop yields and yield stability are increased by increasing in organic matter content, thereby supporting food security (Lal 2006; Pan et al.,2009; Frank et al.,2017;Soussana et al.,2018). 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 (de Moraes Sá et al. 2017; Steinbach et al. 2006) but can be neutral or even negative (Palm et al. 2014; Powlson et al. 2014; Cheesman et al. 2016; Powlson et al. 2016; VandenBygaart 2016), depending on the amount of crop residues returned to the soil. In terms of potential adverse side effects, if soil organic matter stocks are increased by increasing fertiliser inputs to increase productivity, emissions of nitrous oxide emissions from fertiliser use can offset any climate benefits arising from carbon sinks (Gao et al. 2018). Similarly, if any yield penalty is incurred from practices aimed at increasing soil organic matter stocks (e.g., though extensification), emissions could be increased through indirect land use change (Lambin et al.,2010), and there could also be adverse side-effects on food security (Smith,2013).

6.3.1.2 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 and mineral), timing, precision application, inhibitors, use of manures, 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* (see also Section 6.3.1.20) (Lal 2011 Tilman et al. 2011; Smith et al. 2014b; Popelau & Don, 2015).

Improved cropland management can provide moderate to large climate mitigation by reducing greenhouse gas emissions and creating soil carbon sinks in the range of 0.1 $GtCO_2$ yr^{-1} (Chapter 2; (Smith 2008) Smith et al. 2014), with the aggregate potential depending on the balance between atmospheric carbon captured, how much of that carbon returns to the soil, and the enhanced N_2O and CH_4 emissions from nitrogen fertilisers, crop residues and livestock. It is also effective for climate adaptation, for example by improving the resilience of food crop production systems to future climate change (Chapter 2; (Porter et al. 2014). Improving cropland management can help to prevent or reverse desertification by improving sustainable use of land in arid areas (Chapter 3; (Bryan et al. 2009; Chen et al. 2010), and can prevent or reverse land degradation by forming a major component of sustainable land management (Chapter 4; ; (Labrière et al. 2015a). It can also contribute to food security by improving agricultural productivity for food production and closing crop yield gaps (Chapter 5; (Porter et al. 2014).

6.3.1.3 Improved livestock management

Improved livestock management is a collection of practices consisting of a) *improved feed and dietary additives:* to increase productivity and reduce emissions from enteric fermentation; including improved forage, dietary additives (bioactive compounds, fats), ionophores / antibiotics, propionate enhancers, archaea inhibitors, nitrate and sulphate supplements, b) *breeding and other long-term management*: including improved breeds with higher productivity or with reduced emissions from enteric fermentation; microbial technology such as archaeal vaccines, methanotrophs, acetogens, defaunation of the rumen, bacteriophages and probiotics; improved fertility, and c) *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, grazing management (Smith et al. 2014b).

Improved livestock management provides climate mitigation by reducing greenhouse gas emissions, particularly from enteric methane and manure management in the range of 0.5–0.7 $GtCO_2$ yr^{-1} (Chapter 2; Smith et al.,2008, 2014). Improved livestock management can also contribute to climate adaptation by improving the resilience of livestock production systems to future climate change (Chapter 2; Porter et al. 2014; Rojas-Downing et al. 2017). It can help with prevention or reversal of desertification, e.g. through use of more efficient and adapted breeds in arid areas (Chapter 3; (Archer et al.,2011); Miao et al. 2015; Squires et al. 2015)and for for prevention or reversal of land degradation by allowing for reduced stocking density with more efficient breeds (Chapter 4; Tighe et al. 2012). Improved livestock management can also contribute to food security by improving livestock sector productivity for food (Chapter 5; (Herrero et al. 2016).

6.3.1.4 Improved grazing land management

Improved grazing land management is a collection of practices consisting of a) *management of the vegetation*: including improved grass varieties / sward composition, deep rooting grasses, increased productivity, and nutrient management, b) *animal management*: including appropriate stocking densities to fit carrying capacity, fodder banks, and improved grazing management fodder production, and fodder diversification, and c) *fire management*: improved use of fire for sustainable grassland management, including fire prevention and improved prescribed burning (Smith et al. 2014b).

Improved grazing land management is an important response option for climate change mitigation by increasing soil carbon sinks and reducing greenhouse gas emissions in the range of 1.3 $GtCO_2$ yr^{-1} (Chapter 2; Section 6.4; (Herrero et al. 2016 ; Conant et al. 2017). It also has the capacity to contribute to climate adaptation by improving the resilience of grazing lands to future climate change (Chapter 2; Porter et al. 2014;Briske et al. 2015) Improving grazing land management can help to prevent or reverse desertification, for example, by tackling overgrazing in arid areas (Chapter 3; (Archer et al.,2011; Schwilch et al. 2014), and can help to prevent or reverse land degradation by optimising stocking density (Chapter 4; Tighe et al. 2012). Improved grazing land management can deliver improved food security by improving livestock sector productivity for food (Chapter 5; (Herrero et al. 2016).

6.3.1.5 Increased food productivity

Increased productivity of food (which could arise from many other interventions such as improved cropland, grazing land and livestock management) could help in addressing a number of the land challenges, but only if it is achieved in a sustainable way. Many interventions to increase food production, particularly those predicated on very large inputs of agro-chemicals, have resulted in a wide range of negative externalities (e.g., Godfray et al. 2010; Foley et al. 2011b) leading to the proposal of sustainable intensification as a mechanism to deliver future sustainable increases in productivity (see Cross-Chapter Box 5: Agricultural Intensification, Chapter 5; Burney et al. 2010; Smith 2013; Tilman et al. 2011; Garnett et al. 2013). Increasing food productivity could provide climate change mitigation benefits, if land is spared as a result (Lamb et al. 2016; Balmford et al.,2018), but intensification through additional input of nitrogen fertiliser, for example, would result in negative climate impacts through increased emissions of nitrous oxide (Shcherbak et al., 2014). Increased food productivity could confer improved resilience to climate shocks, thereby acting as an adaptation measure (Lobell et al. 2008). Increased food productivity could have positive or negative impacts on both desertification and land degradation. If implemented in a way that over-exploits the land (e.g., through over-grazing; Chapter 3 and Chapter 4), significant negative impacts would occur, but if implemented sustainably, it could provide benefits for both desertification and land degradation (e.g., (Lal 2016). If increased productivity comes from intensified land use, the impact on desertification would be very negative, since intensive agricultural use of land is a key driver of desertification (Chapter 3; IPBES, 2018). However, if increased food productivity were achieved through sustainable intensification, and used to spare land, it could reduce the pressure on land (Balmford et al.,2018), which could have a positive impact on efforts to address desertification (e.g., FAO/IAEA, 2018). Though food security is not only about increased production (Chapter 5), increased food productivity is central to many proposals to improve food security (Godfray et al. 2010b) (Godfray et al. 2010).

6.3.1.6 Agro-forestry

Agroforestry is a sustainable land management practice (Nair et al. 2014) that constitute the deliberate planting of trees in croplands and silvo-pastoral systems (Santiago-Freijanes et. al. 2018). There are multiple benefits of agroforestry practices including at the personal level of the farmer through payment for Nature’s Contributions to People (Benjamin et. al. 2018) and reducing vulnerability to climate shocks). The benefits of agroforestry include its contribution to climate change response in both mitigation and adaptation (Mosquera-Losada et al. 2018). The mitigation benefits include the opportunities in decreasing the level of CO_2 in the atmosphere through sequestration and the accumulation and storage of carbon in agricultural systems as stable sinks (Guo et al. 2018). Putting this in perspective in the land area currently under agroforestry practices, demonstrate its potentials for mitigation. Estimates using Land Use and Land Cover data (LUCAS) shows that the total area under agroforestry in the Europe Union is about 15.4 million ha, representing 3.6% of the territorial area and 8.8% of the area utilised for agricultural production (Herder et al. 2017). The adaptation benefits of agroforestry include biological nitrogen fixation estimated to be in the range of 13–500 kg ha^{-1} yr^{-1} critical for agricultural production (Ram et al. 2017) and increase in soil organic carbon and soil microbial community that enhances climate resilience of agricultural production systems. They offers potentials for the prevention and reversal of desertification and land degradation, particularly through soil improvement (Antwi-Agyei et al. 2014) and restoring Nature’s Contributions to People and resilience important for adaptation (Mbow et al. 2014; Sain et al. 2017; Yirdaw et al. 2017). Diverse farm systems based on The mimicking or restoring natural ecosystems diverse farm systems that have clear benefits for increases in food security (Vignola et al. 2015).

There are some barriers to agroforestry that include the lack of information and reliable financial support (Hernandez-Morcillo et al. 2018). Where agroforestry response options are tailored to Nature’s Contributions to People, some trade-offs have been reported between the provisioning and regulating Nature’s Contributions to People (Kearney et al. 2017). The competition for land between afforestation/reforestation and agricultural production is a potentially large *adverse side-effect* (Boysen et al. 2017a,b; Kreidenweis et al. 2016a;Smith et al. 2013b) Despite, its positive impact on diversification and biodiversity, agroforestry can also have some adverse side-effects, such environmental impacts (excessive N_2O emissions, and disruption of regional GHG balances) with leguminous agroforestry (Rosenstock et al. 2014).

6.3.1.7 Sustainable forest management and forest restoration

Sustainable forest management refers to 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 (Forest Europe 2016). Sustainable forest management includes a wide variety of practices affecting the growth of tress and the biomass removed, including the regeneration (natural or artificial) and the schedule and intensity of operations (thinnings, selective logging, final cut, etc.).

Forest restoration broadly refers to practices aimed at regaining ecological integrity in a deforested or degraded forest landscape (e.g., Stanturf et al. 2015; Dooley and Kartha 2018). As such, it could fall under restoration if it were re-establishing trees where they have been lost, and could be part of forest management if it were restoring forests where not all trees have been lost. For practical reasons, in this chapter, forest restoration is treated together with sustainable forest management.

Sustainable forest management and forest restoration mitigate climate change by conserving and enhancing 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 (Smith 2014; Grassi et al. 2017; Griscom et al. 2017). Sustainable forest management does not necessarily imply that carbon stock remains constant or increases, and trade-offs exist between conserving carbon stocks and raising the contribution of biomass to raw materials and substitution effects (Kurz et al. 2016; Erb et al. 2017). More harvest decreases the carbon in the forest in the short term but increases the carbon in wood products and the potential for substitution effects. The most effective forest carbon mitigation strategy is the one that, through maintaining or increasing biomass productivity, optimises the carbon stocks (in forests and in long-lived products) as well as the wood substitution effects in a given time frame (Smyth et al. 2014a; Nabuurs et al. 2017; Grassi et al. 2018). Forest management affects also albedo and evapotranspiration (Naudts et al. 2016).

Sustainable forest management and forest restoration may facilitate the adaptation and resilience of forests to climate change by enhancing connectivity between forest areas and conserving biodiversity hotspots (Locatelli 2011, 2015; Ellison et al. 2017, Dooley and Kartha 2018). Conserving forest carbon, also through corridors (Jantz et al. 2014), improves ecosystem functionality and services availability, provides microclimatic regulation for people and crops, provides 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. 2015). Forestry-based mitigation measures are more likely to be sustainable and long-lasting if integrated into adaptation measures for communities and ecosystems, for example, through landscape management (Locatelli et al. 2011). Selective logging techniques are “middle way” between deforestation and total protection, allowing to retain substantial levels of biodiversity and carbon (Putz et al. 2012), and can therefore offer potential co-benefits in terms prevention of land degradation.

Forest management strategies aiming at increasing the biomass stocking levels may also have *adverse side-effects*, decrease stand-level structural complexity, biodiversity and the adaptation potential (D’Amato et al. 2011; Locatelli et al. 2011), and may make forest ecosystems less resilient to natural disasters like wind throws, fires, and diseases (Seidl et al. 2014). Forest restoration may threaten livelihoods local access to land if subsistence agriculture is targeted (Dooley and Kartha 2018).

6.3.1.8 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 the economic risks posed by fluctuating market forces. In general, the agricultural system is moved from one based on low-value agricultural commodities to another that is more diverse, composed of a basket of higher value-added products (e.g., Lipper et al. 2014; Waha et al. 2018). It is targeted at adaptation (Campbell et al. 2014; Cohn et al. 2017), and depending on how it is implemented (e.g., if planting more perennials such as fruit trees), could also deliver a small carbon sink. It could help with prevention of desertification and land degradation since it can reduce the pressure on land (Lambin and Meyfroidt 2011), and will help with the achievement of food security (e.g., Birthal et al. 2015; Massawe et al. 2016; Waha et al. 2018), as well as household income (Pellegrini and Tasciotti 2014). There are likely few adverse side effects (Massawe et al. 2016; Waha et al. 2018a). Potential of agricultural diversification to achieve household food security is influenced by, the market orientation of a household, livestock ownership, nonagricultural employment opportunities, and available land resources, and it regognises certain limits in terms of level of diversity per hectare cropland and feasibility to purchase food from off-farm income or income from farm sales (Waha et al. 2018).

6.3.1.9 Management of 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 (FAO and ITPS 2015). Soil erosion management includes conservation practices such as the use of minimum tillage or zero tillage (Derpsch et al. 2010; de Moraes Sá et al. 2017), crop rotations and cover crops, rational grazing systems, among others (Poeplau and Don 2015) and also engineering-like practices such as construction of terraces and contour cropping for controlling water erosion, or forest barriers and strip cultivation for controlling wind erosion (Chen 2017). In eroded soils, the advance of erosion gullies and sand dunes can be limited by revegetation, among other practices. The fate of eroded soil carbon is not certain, with some studies suggesting that it acts as a net source of CO_2 to the atmosphere (Jacinthe and Lal 2001, Lal et al., 2004), while other studies suggest it results in a net sink (Stallard 1998;Smith et al. 2001;Smith et al. 2005; Van Oost et al. 2007). Management of erosion, is however, an important climate change adaptation measure, since it makes soil less vulnerable to loss under climate extremes, thereby increasing resilience to climate change (Garbrecht et al. 2015). Some management practices implemented to control erosion, such as increasing ground cover, can reduce the vulnerability of soils to degradation / landslides (FAO et al. 2015), and prevention of soil erosion is a key measure used to tackle desertification (Chapter 3; (FAO et al. 2015). Since prevention of erosion protects the capacity of land to produce food, it also contributes positively to food security (Lal and Moldenhauer 1987). Management of soil erosion has no adverse side-effects.

6.3.1.10 Prevention / reversal of soil salinisation

Soil salinisation is a major process of land degradation that decreases soil fertility, is a significant component of the desertification process for the world's drylands, and affects agricultural production, aquaculture and forestry, and can also affects large surfaces of lowlands. Prevention of soil salinisation can be achieved through improvement of water management including water-use efficiency and irrigation/drainage technology in arid/semi-arid areas, surface and groundwater management in lowlands, improvement of soil health through increase in soil organic matter content and improving cropland and livestock management, agroforestry, grazing management, and conservation agriculture (Dagar et al. 2016b; Evans and Sadler 2008; He et al. 2015; UNCTAD 2011; DERM 2011; Rengasamy 2006; Baumhardt et al. 2015; Datta et al. 2000; Prathapar 1988).

Techniques to prevent and reverse soil salinisation may have a small benefit for mitigation since they may benefit soil carbon sinks (Section 6.3.1.1), and may benefit adaptation, since they allow existing crop systems to be maintained (Wong et al. 2010; Qadir et al. 2013 ; UNCTAD 2011; Dagar et al. 2016). Techniques to prevent and reverse soil salinisation are central to the prevention and reversal of desertification (Chapter 3, Section 3.6,; Rengasamy 2006; Dagar et al. 2016) and land degradation, since soil salinisation is a main driver of both desertification and land degradation in the world's drylands (Chapter 4, Section 4.8; Rengasamy 2006; Dagar et al. 2016). Prevention of soil salinisation may also benefit food security by maintaining existing crop systems, and helping to close yield gaps in rainfed crops (Chapter 5, , Section 6.5 this Chapter). There are likely to be few adverse side-effects, apart from potential additional fossil fuel use for irrigation.

6.3.1.11 Prevention of compaction

Prevention of soil compaction is mainly based on agricultural techniques (e.g., crop rotations, control of livestock density) and control of agricultural traffic (Soane and van Ouwerkerk 1994; Hamza and Anderson 2005; FAO et al. 2015).

Techniques to prevent and reverse soil compaction may be neutral of have small benefits for mitigation due to variable impacts on GHG emissions. Prevention of compaction may also benefit adaptation by improving soil climatic resilience (Tim Chamen et al. 2015; Epron et al. 2016; Tullberg et al. 2018). Prevention of soil compaction can deliver large benefits for prevention and reversal of land degradation and large benefits for prevention and reversal of desertification, since soil compaction is a main driver of both desertification and land degradation (Hamza and Anderson 2005; FAO and ITPS 2015) . Prevention of compaction could deliver moderate benefits for food security by helping to close yield gaps in rainfed crops (Anderson and Peters 2016). Implementation costs are not high since compaction avoidance technologies require less fuel and provide a win–win strategy for farmers and the environment (Tim Chamen et al. 2015). There are likely to be few adverse side-effects.

6.3.1.12 Fire management

Fire management is a land management option aiming at the safeguarding of life, property and resources through the prevention, detection, control, restriction and suppression of fire in forest and other vegetation in rural areas (FAO 2006). It includes the improved use of fire for sustainable forestry management, including wildfire prevention and improved prescribed burning (Smith et al. 2014b). Prescribed burning is used to reduce the risk of large, uncontrollable fires breaking out in forest areas, and controlled burning is among the most effective and economical methods of reducing fire danger and stimulating a natural reforestation process under the forest canopy and after clear felling (Valendik et al. 2011). The frequency and severity of large wildfires have increased around the globe in past decades, and it strongly impacts forest carbon budgets (Seidl et al. 2014; Westerling et al. 2006). For example, the disturbance-related reduction (including wildfires, pests and wind) of the carbon storage potential in Europe's forests is estimated to be 503.4 Tg C in 2021–2030 (Seidl et al. 2014).

Fire can cause various greenhouse gas emissions such as CO_2, CH_4, and N_2O, and others such as CO, volatile organic carbon, and smoke aerosols (O'Mara,2012). Total emissions from fires have been in the order of 1.75 $GtCO_2$ (Tacconi 2016), thus, fire management provides co-benefits to climate change mitigation (Whitehead et al. 2008). Control of fire enhances adaptation capacity, since haze pollution over the past four decades in Southeast Asia was mainly a result of forest- and peatland-fire in Indonesia (Lin et al. 2017), and transboundary haze pollution as a result of fire has significant health and economic impacts on member states of the Association of South-east Asian Nations (ASEAN) (Yong et al. 2014). Fire management is one of the main options for preventing soil erosion and land degradation (Esteves et al. 2012). Around 50,000 wildfires affect, on average, 600,000 ha of mainly forests and shrubland in the southern European Mediterranean countries (Rulli et al. 2006). Furthermore, fire management is one of essential livestock managements in many rangelands to conserve biodiversity and to enhance forage quality (Scasta et al. 2015). However, reduction in fire frequency has a potential of some adverse side effects, since fire can be used to control and improve production in pastures (O'Mara 2012).

6.3.1.13 Management of landslides and natural hazards

Landslide occurrence is 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 practices (e.g., afforestation) and enginnering works (e.g., dams, terraces, stabilisation and filling of erosion gullies).

The prevention and management of landslides and natural hazards would be expected to be neutral or deliver only small global benefits for mitigation, since it has little impact of GHG emissions or on eventual preservation of topsoil carbon stores, but it is very important for adaptation (IPCC AR5 WG2, Chapter 14; Noble et al. 2014;Gariano et al. 2016). Management of landslides and natural hazards would be expected to be neutral or be slightly beneficial for managing desertification, but it is a very important intervention for managing land degradation, since landslides and natural hazards are among the most severe degradation processes (Arnáez et al. 2015 ; FAO and ITPS 2015). In countries in which mountain slopes are cropped for food crops, such as the case of Pacific Islands (Campbell 2015), the management and prevention of landslides can also deliver some benefits for food security. There are few adverse impacts from measures to reduce the risk of landslides and natural hazards. Most of the deaths caused due to different disasters have occurred in developing countries, in which poverty, poor education and health facilities and other aspects of human population increase exposure and high levels of vulnerability and risk (Mal et al. 2018).

6.3.1.14 Ecosystem-based adaptation

Ecosystem-based adaptation (EbA) involves the use of natural ecosystems and capital to assist in adaptation to climate change, based on the principle that intact and healthy ecosystems are more resilient to climate stressors (Scarano 2017). EbA is intended to provide resilience to climate change and simultaneously to reduce poverty, protect or restore biodiversity and Nature's Contributions to People, and remove atmospheric greenhouse gases (mitigation), and thus is promoted as a win-win with low adverse side effects (Munang et al. 2013). Response options within EbA include targeted management, conservation, and restoration activities, such as protecting or increasing the extent of an ecosystem, enhancing connectivity, protecting or restoring natural 'infrastructure' like barrier islands or coral reefs for disaster risk reduction, or reducing stressors on ecosystems to enhance Nature's Contributions to People. Examples of benefits from such actions include mangrove protection leading to buffers against storm surges or protecting floodplains to recharge groundwater supplies and provide low-cost wastewater treatment (Ojea 2015; Munang et al. 2013).

A recent study (Griscom et al. 2017a) has highlighted the mitigation co-benefits of ecosystem restoration and management for carbon sequestration, as many of the interventions proposed to deliver EbA overlap considerably with those proposed for climate mitigation, particularly those that involve planting trees, sustainable agriculture and coastal, wetland and peatland restoration/management. Some actions might also reduce emissions of non-CO_2 GHGs (e.g., sustainable agricultural management; Lipper et al. 2014), while others (particularly wetland restoration) might temporarily increase methane emissions (Mitsch et al. 2012). In terms of adverse side-effects, large scale afforestation for EbA might increase albedo, particularly at high latitudes (Betts, 2000), and could also affect hydrological cycles with potential climate impacts (Zhao and Jackson 2014).

The prevention of soil erosion is part of EbA (Munang et al. 2013), and decreased erosion rates make soils and vulnerable arid ecosystems less vulnerable to desertification (D'Odorico et al. 2013a). Ecological restoration and use of natural / green infrastructure, might also provide vegetation at the margins of areas under threat of desertification, which might slow or halt the process (D'Odorico et al. 2013a). Improved cropland management (reduced tillage intensity) and grazing land management (reduction of overgrazing), and improved irrigation provision of water to arid areas) might also help to prevent desertification (D'Odorico et al. 2013a). Ecological restoration of forest, grasslands, coastal ecosystems, wetland and peatlands for EbA clearly also provide actions to halt and reverse land degradation (Griscom et al. 2017a). EbA can also be also take the form of sustainable agricultural management (Shaw et al. 2014), and when applied in this way can also improve food supply, thereby contributing to improved food security (Shaw et al. 2014). Diverse farm systems based on mimicking or restoring natural ecosystems (i.e., as in some agroforestry systems) have clear benefits for increases in food security (Vignola et al. 2015). Adverse side-effects may arise when ecosystems are restored on land currently used for food production, and/or some reduced yields in EbA-based agricultural systems given trade-offs (Vignola et al. 2015). Large areas of tropical peatlands have been drained and cleared for food production (Page et al. 2011) and their restoration could displace food production and damage local food supply in these areas. The same is true for cultivated northern peatlands (Grønlund et al. 2006). The restoration of coastal habitats (e.g., mangroves) could also complete with local fisheries and aquaculture, having local impacts on food supply and livelihoods (Bush et al. 2010).

EbA's strengths are that it is often more flexible and cost-effective than other approaches to adaptation like infrastructure development, and more reversible (Jones et al. 2012; Ojea 2015). However, there have been few assessments of the degree to which EbA approaches are integrated into either national or subnational projects and policies, and the limited country experience to date shows that many challenges remain in operationalising EbA (Vignola et al. 2009; Chong 2014), namely due to policy barriers and scalability issues (Ojea 2015; Scarano 2017).

6.3.1.15 Reduced deforestation and forest degradation

Reduced deforestation and forest degradation include 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 wildfires), avoiding the loss of high carbon forests, establishing protected areas and improving enforcement, improving land tenure and introducing forest certification (Hosonuma et al. 2012 ;Curtis et al. 2018).

Since deforestation and forest degradation represent a major source of emissions globally (Baccini et al. 2017, see Chapter 2), they also have a high mitigation potential (Griscom et al. 2017), especially if combined with forest regrowth (Houghton et al. 2015). Because of the biophysical effects of deforestation (e.g., on albedo and evapotranspiration), reduced deforestation have the major climate mitigation effect in the tropics (Alkama and Cescatti 2016).

Reduced deforestation and forest degradation have important *co-benefits* with ecosystem resilience, biodiversity conservation and other Nature's Contributions to People, especially in the species-rich ecosystems in tropics (Lewis et al. 2015, Dooley and Kartha 2018, Barlow et al. 2016) where deforestation and forest degradation rates are usually high (Hansen et al. 2013). Reduced deforestation preserves biodiversity more efficiently and at lower costs than afforestation/reforestation (Rey Benayas et al. 2009).

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 (Caplow et al. 2011; Few et al. 2017).

6.3.1.16 Management of pollution including acidification

Management of air pollution and climate change are connected starting from emission sources of air polluting materials to their impacts on climate, human health, and ecosystems, including agriculture (Melamed et al. 2016). 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 (Smith et al. 2015). Practices that reduce acid deposition include prevention of emissions of nitrogen oxides (NOx) and sulphur dioxide (SO_2), which would also reduce greenhouse gas emissions and other Short-Lived Climate Pollutants (SLCPs) (Nemet et al. 2010). Management of harmful air pollutants such as fine particulate matter (PM2.5) and ozone (O_3) would also mitigate the impacts of fossil fuel combustion and greenhouse gas emissions (Markandya et al., 2018). In addition, management of pollutants such as tropospheric O_3 would have beneficial impacts on food production, as it would limit ozone which decreases crop production (Carter et al. 2015). Finally, since acidification in ocean, coastal and freshwater, caused by air pollution, rising atmospheric CO_2, acid deposition, and industrial waste increases vulnerability in marine and freshwater ecosystems (Mostofa et al. 2016), management of pollution would also contribute to aquatic ecosystem conservation. Thus, control of urban and industrial air pollution would mitigate the harmful effects of pollution and provide adaptation co-benefits *via* improved human health (Anderson et al. 2017).

There are, however, also some potential adverse side effects of management of air pollution to carbon sequestration in terrestrial ecosystems. Reactive nitrogen deposition could enhance CO_2 uptake in boreal forests and increase soil carbon pools to some extent (Maaroufi et al. 2015). It might also have some adverse side effects on food production, since some forms of air pollutants could actually enhance crop productivity by increasing diffuse sunlight, compared to direct sunlight (Wild et al. 2012). Air pollutants have different impacts on climate, with some air pollutants (e.g., aerosols at the top of the atmosphere) increasing the reflection of solar radiation to space leading to net cooling (Ramanathan et al. 2001), while others (e.g., nitrogen oxides; Seinfeld and Pandis, 2006) having a net warming effect.

Therefore, control of these different pollutants will have both positive (co-benefits) and negative (adverse side effects) impacts on climate mitigation (Coakley, 2005).

6.3.1.17 Management of invasive species including encroachment

Agricultural and forests can be very high in diversity but much of it is often non-native. Invasive species in different biomes have been introduced through intended and unintended processes of exportation of ornamental plants or animals, and many times through the promotion of modern agriculture and forestry. Non-native species tend to be more numerous in larger than smaller human-modified landscapes (e.g., over 50% of species in an urbanised area or extensive agricultural field can be non-native). Management of invasive species can be done through manual clearance of invasive species, which has been done in many landscapes, while in some areas natural enemies of the invasive species are introduced to control them (Dresner et al. 2015).

Exotic species are used in forestry and for afforestation as an alternative in many places 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 (Brundu, Richardson, 2016). In general, exotic species have growing rates much greater than native species; therefore, they produce more wood per unit of area and time (mean of annual increment of fast growing exotic species is equal 10–40 m^3 ha^{-1} yr^{-1} (Cossalter and Pye-Smith 2003). With features as fast growing and wider adaptation, exotic species could be used as source of different type of products and so reduce the pressure over native species (Payn et al. 2015). In 2015, the total area of planted forest with non-native tree species was estimated to around 50 million ha in 2015 (Payn et al., 2015). Introduced species were dominant in the countries of South America, Oceania and Eastern and Southern Africa where industrial forestry is dominant (Payn et al., 2015). 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, negative impacts and without compromising future benefits and land uses. 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).

According results of meta-analysis abundance and diversity of the native species decreased in communities with domination of invasive species, whereas primary production and several ecosystem processes were enhanced (Vilà et al. 2011). While alien N-fixing species had greater impacts on N-cycling variables, they did not consistently affect other impact types (Vila et al. 2011).

Invading alien species in the United States cause major environmental damages and losses adding up to almost $120 billion per year (Pimentel et al., 2005). 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 (Pimentel et al., 2005).

6.3.1.18 Reforestation

Reforestation is conversion of land that was recently deforested to forest, often with a conservation or landscape protection background, generally focusing on restoration of ‘‘nature-like’’ ecosystems (Reyer et al., 2009). Reforestation also includes improved biomass stocks by planting trees on non-forested agricultural lands that were previously forested (see also afforestation for non-forest land) and can include either monocultures or mixed species plantings (Smith et al., 2014).

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 Section 6.3.1.22 Afforestation).

6.3.1.19 Restoration and avoided conversion of coastal wetlands

Coastal wetland restoration involves restoring degraded / damaged coastal wetlands including mangroves, salt marshes and seagrass ecosystems, which has the capacity to increase carbon sinks (Griscom et al. 2017a). Coastal wetland restoration and avoided coastal wetland impacts could provide substantial benefits for climate mitigation (Griscom et al. 2017). Coastal wetland restoration may also provide significant benefits for climate adaptation by regulating water flow and preventing downstream flooding (Munang et al. 2014); they provide a natural defence against coastal flooding and storm surges by dissipating wave energy, reducing erosion and by helping to stabilise shore sediments. There are likely no benefits nor adverse side effects of coastal wetland restoration for prevention of desertification, since these do not occur in arid areas. Since large areas of global coastal wetlands are degraded (Lotze et al. 2006; Griscom et al. 2017a), restoration could provide large benefits for preventing and reversing land degradation. Since some areas of coastal wetlands are used for food production (e.g., mangroves converted for aquaculture; Naylor et al. 2000), restoration could displace food production and damage local food supply (Section 6.4.4), potentially leading to a small adverse impacts on food security, though the impact may be more significant in the affected areas than globally. This could be offset by more careful management, such as the careful siting of ponds within mangroves (Naylor et al. 2000).

6.3.1.20 Biochar

The use of biochar, the solid by -product of the pyrolysis process, for the production of bioenergy as a soil amendment increases the water-holding capacity of soil (Laird et al., 2010) and 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 Smith, 2016), amongst other potential benefits discussed in Chapter 4. Use of biochar as a soil amendment can provide significant mitigation by creating soil carbon sinks (Smith 2016), and could also provide benefits for 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 (Chapter 2; Woolf et al. 2010; Sohi 2012). Biochar could potentially benefit prevention or reversal of desertification and of land degradation, in both cases by improving water holding capacity, improving nutrient use efficiency, managing heavy metal pollution and other impacts (Chapter 3; Chapter 4; Sohi 2012). There may be, on balance benefits for food security from improved yield in the tropics but less so in temperate regions (Jeffery et al. 2017), through improved water holding capacity and nutrient use efficiency (Chapter 5; Sohi 2012), though these co-benefits could be tempered by additional pressure on land if large quantities of biomass are required as feedstock for biochar production, causing potential conflicts with food security (Smith 2016a). There are few adverse impacts across the challenges, other than the land requirement for biomass feedstock (Smith 2016a).

6.3.1.21 Restoration and avoided conversion of peatlands

Peatland restoration involves restoring degraded / damaged peatlands which both increases carbon sinks, but also avoids the ongoing CO_2 emissions from degraded peatlands, so it both prevents future emissions and creates a sink (Griscom et al. 2017). Avoided peat impacts and peatland restoration can provide significant mitigation (Griscom et al. 2017), though there could be a temporary increase in methane emissions after restoration (Jauhiainen et al. 2008). There may also be benefits for climate adaptation by regulating water flow and preventing downstream flooding (Munang et al. 2014). There are likely ***no benefits*** nor adverse impacts of peatland restoration on efforts to prevent or reverse desertification, as peatlands occur in wet areas and deserts in arid areas so they are not connected. Considering that large areas of global peatlands are degraded (Limpens et al. 2008), peatland restoration provides significant benefits for preventing and reversing 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.

6.3.1.22 Afforestation

Afforestation includes practices to increase standing biomass stocks by planting trees on non-forested agricultural lands that have not previously been forested (see also reforestation for planting on former forest land) and can include either monocultures or mixed species plantings (Smith et al., 2014).

Afforestation mitigates climate change by increasing terrestrial carbon stocks and capturing atmospheric CO_2 (Ciais et al., 2013). However, afforestation also changes the physical properties of land surfaces, such as surface albedo and evapotranspiration (Bonan, 2008), with implications for the local and global climate system (Perugini et al., 2017). There is a clear latitudinal pattern in the biophysical climate response to afforestation (Alkama and Cescatti, 2016; Arora and Montenegro, 2011; Li et al., 2015; Cherubini et al.,2017). In the tropics, enhanced evapotranspiration contributes to cool surface temperature and reinforce the climate benefits of CO_2 sequestration in trees. On the other hand, at higher latitude, or 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 have seasonal variability and mitigate frequency of climate extremes such as heat waves (see Chapter 2) (Findell et al., 2017; (Lejeune et al.,2018), thereby improving adaptation to climate change and reducing the vulnerability of people and ecosystems (Ellison et al., 2017; Kongsager et al., 2016; Locatelli et al., 2015). Afforestation measures have significant co-benefits and synergies with contrasting land degradation and desertification (see Chapter 3 and Chapter 4), as forests tend to maintain water quality by reducing runoff, trapping sediments and nutrients, and improve groundwater recharge (Idris Medugu et al. 2010; Salvati et al., 2014). However, there are large adverse side-effects between afforestation and food security (see Chapter 5), because an increase in global forest area can lead to increases in food prices through land competition (Boysen et al., 2017; Boysen et al., 2017; Kreidenweis et al., 2016; Smith et al., 2013). Other adverse side-effects across a range of land challenges occur when afforestation is based on non-native species, especially with the risks related to the spread of exotic fast growing tree species (Brundu and Richardson, 2016; Ellison et al., 2017). For example, exotic species can upset the balance of evapotranspiration regimes, with negative impacts on water availability, particularly in arid regions (Ellison et al., 2017; Trabucco et al., 2008).

6.3.1.23 Avoidance of conversion of grassland to cropland

Since croplands have a lower soil carbon content than grasslands and are also more prone to erosion than grasslands, avoidance of conversion of grassland to croplands will prevent soil carbon losses by oxidation and soil loss through erosion. Avoidance of conversion of grassland to cropland could provide climate mitigation by retaining soil carbon stocks that might otherwise be lost. Historical losses of soil carbon have been on the order of 500 $GtCO_2$ (Sanderman et al. 2017). Mean annual global cropland conversion rates (1961–2003) have been 0.36% per year (Krause et al. 2017), that is, around 4.7 Mha yr^{-1} – so preventing conversion could potentially save significant emissions of CO_2. There could be some benefits for adapation in terms of stabilising soils to improve resilience (Lal 2001), or adverse impacts by limiting the capacity of farmers to adapt to future challenges (i.e., no possibility to convert grassland to grow crops). Since shifting from grassland to tilled crops increases erosion and soil loss, there are significant benefits for prevention or reversal of desertification, by stabilising soils in arid areas (Chapter 3), and large benefits for prevention or reversal of land degradation through the same mechanism (Chapter 4). There are likely to be adverse impacts on food security, since conversion of grassland to cropland usually occurs to remedy food security challenges, and much more land is required to produce human food from livestock products on grassland than from crops on cropland (Chapter 5; de Ruiter et al. 2017; Clark and Tilman 2017).

6.3.1.24 Enhanced weathering of minerals

The enhanced weathering of minerals that naturally absorb CO_2 from the atmosphere has been proposed as a greenhouse gas removal technology (Smith et al. 2016, Taylor et al. 2016) with a large mitigation potential ((Lenton 2010; Smith et al. 2016a; Taylor et al. 2016). 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 (Schuiling and Krijgsman 2006). Enhanced mineral weathering would not be expected to impact adaptation or desertification, but since ground minerals can increase pH (Taylor et al. 2016b), there could be some benefits for efforts to prevent or reverse land degradation, where acidification is the driver of degradation (Taylor et al. 2016b). Since increasing soil pH in acidified soils can increase productivity, the same effect could provide some benefit for food security (Taylor et al. 2016b). 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, so there are likely to be a small adverse impact of mining globally.

6.3.1.25 Bioenergy and BECCS

Bioenergy production can mitigate climate change by delivering an energy service, therefore avoiding combustion of fossil energy (see Chapter 2). It is the most common renewable energy source used today in the world and the one with the largest future potential deployment (Creutzig et al. 2015; Edenhofer et al. 2011; Slade et al. 2014). Bioenergy with CO_2 Capture and Storage (BECCS) entails the use of bioenergy technologies (e.g., bioelectricity or bioliquids) in combination with CO_2 capture and storage (see also Glossary). BECCS simultaneously provides energy and reduces atmospheric CO_2 concentrations. Note that while five BECCS demonstration projects exist (Torvanger 2018), it has yet to be deployed at scale (Kemper 2015); see Section 6.5 and Chapter 7 for a further discussion of barriers to BECCS deployment.

Bioenergy and BECCS are widely-deployed in many future scenarios as a climate change mitigation option in the energy and transport sector (Edenhofer et al. 2011, Chum et al. 2011; Clarke et al. 2014; Creutzig et al. 2015; IPCC SR1.5; Riahi et al. 2017; Edelenbosch et al. 2017; Popp et al. 2011; Sims et al.,2014) especially those aiming at a stabilisation of global climate at 2°C or less (Edelenbosch et al. 2017 ; Popp et al. 2014, 2017; van Vuuren et al. 2016; Van Vuuren et al. 2010; IPCC SR1.5; van Vuuren et al. 2011).

Bioenergy and BECCS, however, compete for land and water with other uses. Increased use of bioenergy and BECCS can result in large expansion in cropland area (Popp et al. 2017; Calvin et al. 2014; Smith et al. 2016), and in increased irrigation water use and increased water scarcity (Chaturvedi et al. 2013; Popp et al. 2011; Smith et al. 2016; Fuss et al. 2018; Hejazi et al. 2015b) Bioenergy demands can result in increased food prices (Muratori et al. 2016; Favero and Mendelsohn 2017; Calvin et al. 2014a; Popp et al. 2017; Fuss et al. 2018; Lotze-Campen et al. 2013; Vuuren et al.,2015; Popp et al. 2011; Fuss et al. 2018; Obersteiner et al. 2016b) and can lead to an increase in the population at risk of hunger (Fujimori et al. 2018). As a result of these effects, bioenergy and BECCS can have negative impacts for food security.

Interlinkages of bioenergy and BECCS with climate change adaptation, land degradation and desertification 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 it 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 (FAO, 2011; Lal, 2014). However, with low inputs of fossil fuels and chemicals, limited irrigation, heat/drought tolerant species, using marginal land, biofuel programs can be beneficial to future adaptation of ecosystems (Dasgupta et al. 2014; Noble et al. 2014). Bioenergy crops like perennial grasses can increase soil carbon and improve many indicators related to ecosystem quality (including biodiversity) (Robertson et al. 2017; Sánchez et al. 2017; Kemper 2015; Mello et al. 2014; Fuss et al. 2018; Don et al. 2012b) thereby helping to preserve soil quality, reverse land degradation, and prevent desertification processes.

These effects are also scale and feedstock dependent. Large-scale production of bioenergy can require significant amounts of land (Smith et al. 2016a; Popp et al. 2017), 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 (see also Section 6.5); however, these land requirements could still be substantial. In terms of feedstocks, the use of residues (Kemper 2015) or woody bioenergy (Fuss et al. 2016) could limit competition for land. However, some studies suggest that the additional forest needed for woody bioenergy could compete with farmland (Favero and Mendelsohn 2017).

6.3.2 Integrated response options based on value chain management

6.3.2.1 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 overconsumption (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 an decline in undernourishment (Godfray et al. 2010), as well as reduction in the risk of mortality due to over-consumption (Aleksandrowicz et al. 2016 ; Tilman and Clark 2014a).

A dietary shift away from meat can reduce greenhouse gas emissions (Stehfest et al. 2009; Bajželj et al. 2014a; Muller et al. 2017a; Bonsch et al. 2016; Aleksandrowicz et al. 2016; Havlík et al.,2014) reduce cropland and pasture requirements (Stehfest et al. 2009; Bajželj et al. 2014a; Aleksandrowicz et al. 2016b; Haberl et al. 2011; Erb et al. 2016a), reduce mitigation costs (Stehfest et al. 2009) and increase bioenergy potential, resulting in contributions to mitigation (see also Chapter 5). By decreasing pressure on land (Smith 2013), demand reduction through dietary change and waste reduction could allow for decreased production intensity (Muller et al. 2017a), which could reduce soil erosion and provide benefits to a range of other environmental indicators such as deforestation, and decreases in use of fertiliser (nitrogen and phosphorus), pesticides, water and energy (Muller et al. 2017a), leading to potential benefits for adaptation, desertification, and land degradation.

6.3.2.2 Reduced post-harvest losses

Post-harvest food losses underlie the food system's failure to equitably enable accessible and affordable food in all countries (Wilhelm et al. 2016). Improving post-harvest food losses has can improve food security in developing countries with *high confidence* and *medium agreement* (Hodges et al. 2011). Approximately one-third of the food produced for human consumption is wasted in postproduction operations (Bradford et al. 2018) Gustavsson et al. 2011). Kumar & Kalita (2017) estimates that most of these losses are due to poor storage management. Food loss in developed countries mostly occurs at the retail/consumer stage (Bajželj et al. 2014a; Göbel et al. 2015) – this is dealt with in section Chapter 5. In developing countries, food loss occurs mainly at the post-harvest stage, and less at consumption stage (Ritzema et al. 2017). The key drivers for post-harvest waste in developing countries are structural and infrastructure deficiencies (Chaboud and Daviron 2017; Sheahan and Barrett 2017). 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 (Bajželj et al. 2014a; Ritzema et al. 2017). Differences exist between farm food waste reduction technologies between small-scale agricultural systems and large scale agricultural systems (Ansah et al. 2017; Hengsdijk and de Boer 2017). A suite of options includes farm level storage facilities, trade or exchange processing technologies including food drying, onsite farm processing for value addition, and seed systems which take from harvests. 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 (Kumar and Kalita 2017). Improving and expanding the 'dry chain' can significantly reduce food losses at the household level (Bradford et al. 2018). 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' (Bradford et al. 2018). Regional and local food systems are now being promoted to enable production, distribution, access and affordability of food (Billen et al. 2018; Kissinger et al. 2018). Reducing post-harvest losses has the potential to reduce emissions which could simultaneously reduce food costs and increase availability (Ingram et al., 2016). The perishability and safety of fresh foods are highly susceptible to temperature increase. (Ingram et al., 2016) estimated a 50% reduction in bacterial growth for every 1°C drop in temperature below 10°C. Higher temperatures could increase the presence of pathogens and the challenge of managing food safety (Ingram et al.,2016). Emissions attributable to food waste and loss amount to 3.3 $GtCO_2$-eq yr^{-1} with a large share of this loss in developing countries (Chapter 5).

6.3.2.3 Reduced food waste (consumer or retailer)

Approximately 30% of all food is wasted (Kummu et al. 2012; Gustavsson et al. 2011; Vermeulen et al. 2012a). Reducing food waste can result in a reduction in cropland area and GHG emissions (Bajželj et al. 2014a; Muller et al. 2017a), resulting in benefits for mitigation. By decreasing pressure on land (Smith 2013), demand reduction through waste reduction could allow for decreased production intensity (Muller et al. 2017a), which could reduce soil erosion and provide benefits to a range of other environmental indicators such as deforestation, and decreases in use of fertiliser (nitrogen and phosphorus), pesticides, water and energy (Muller et al. 2017a), leading to potential benefits for adaptation, desertification, and land degradation. A reduction in food waste could provide significant benefits for freshwater provision and nutrient cycling (Kummu et al. 2012).

6.3.2.4 Promotion of value-added products

Value-added food production is a collection of practices that enable producers to increase the economic value or reduce risks of commodities through production processes (e.g., packaging, processing, cooling, drying, extracting). Adding value to products requires improved innovation, coordination and efficiency in the food supply chain (Chapter 5; Section 6.4; Garnett, 2011; Godfray et al., 2010; Hertel, 2015). Promoting value-added products can reduce the need for compensatory extensification of agricultural areas (Chapter 2; Section 6.4; (Bajželj et al. 2014); energy use in pre and post-harvesting processes (Chapter 5; Section 6.4; Accorsi et al. 2017); and emissions from food loss and waste (e.g., methane from landfills) (Ingram et al.;James and James 2010). This response option also provides substantial benefits for climate adaptation 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 (Chapter 5; Section 6.4; Muller et al. 2017). 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. Promoting value-added product could provide significant benefits for food security (Chapter 5; Section 6.4; Tilman and Clark 2014). Value-added products may 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 of resources in the food system potentially leading to a small adverse impacts on land degradation and desertification challenges (Chapter 3; Section 6.4; (Clark et al., 2017).

6.3.2.5 Stability of food supply

Trade driven food supply chains are becoming increasingly complex and contributing to emissions (Chapter 5; Wilhelm et al. 2016). Additionally, globalised food systems and commodity markets are vulnerable to food price volatility (Lewis and Witham 2012), as was seen in the 2007–2008 food price shocks that negatively affected food security for millions, most severely in Sub-Saharan Africa (Wodon and Zaman 2010; The World Bank 2011; Haggblade et al. 2017). Export bans and competition with land for biofuels also likely contributed to price shocks. Increasing the stability of food supplies is a key goal to increase food security, given that climate change threatens to lead to more production shocks in the future (Wheeler and von Braun 2013). Measures to improve stability of food supply in traded markets can include a range of options, such as: 1) financial and trade policies, such as reductions on food taxes and import tariffs; 2) shortening food supply chains (SFSCs); 3) increasing food production; 4) designing alternative distribution networks; 5) increasing food market transparency and reducing speculation in futures markets; 6) increasing storage options; and 7) increasing subsidies and food-based safety nets (Mundler and Rumpus 2012; Barthel and Isendahl 2013; Wodon and Zaman 2010; Michelini et al. 2018; Minot 2014; Tadasse et al. 2016). While policies to regulate prices and stability of food supply have little impact on mitigation measures, they are usually directed at adaptation and food security outcomes, where they have shown promise but in inconclusive ways (Wodon and Zaman 2010).

6.3.2.6 Improved food transport and distribution

Improved food transportation and distribution are a collection of practices geared towards a) improving energy-efficiency (to reduce GHG emissions and simultaneously improve availability and affordability of food), (b) reducing food loss and waste and (c) minimising risk to human health. Strategies such as weatherproofing transport systems, distribution infrastructure and improving the efficiency of food trade (Chapter 2; Section 6.4; (Ingram et al., 2016; Stathers et al. 2013) especially in countries with inadequate infrastructure and weak food distribution systems (Puma et al. 2015; Wellesley et al.; Vermeulen et al. 2012), can strengthen climate resilience against future climate-related shocks (Ingram et al.,2016; Stathers et al. 2013)with potential benefits for climate adaptation. Improved food transportation and distribution can reduce food waste and the need for compensatory extensification of agricultural areas thereby reducing the risk of overexploitation and provide benefits for land degradation and desertification (Stathers et al. 2013). Improved storage and distribution systems can provide substantial benefits for food and nutrition security. The perishability and safety of fresh foods are highly susceptible to temperature increase and are directly linked to household level food security and the well-being of producers (Stathers et al. 2013). Improving and expanding the 'dry chain' can significantly reduce food losses at the household level (Bradford et al.,2018). Technical, organisational and climate communication innovations can improve food storage and distribution in poorer countries and reduce losses substantially (Kumar and Kalita 2017).

6.3.2.7 Urban food systems

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, *medium evidence* with *high agreement* (Brinkley et al. 2016; Specht et al. 2014; Specht et al. 2014; Lee-Smith 2010). Comprehensive urban food systems have a *high likelihood* with *medium confidence* in mitigating climate change through production, distribution and access systems that would reduce direct and embedded emissions but also contribute to adapting to the impacts of climate change (Barthel and Isendahl 2013; Benis and Ferrão 2017). 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 (UPAF; Tao et al. 2015; Lwasa et al. 2014) and local food policy and planning initiatives such as Food Policy Councils and city-region-wide regional food strategies (Brinkley et al. 2013; Chappell et al. 2016). 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 (Akhtar et al. 2016) (Lee-Smith 2010; Revi et al. 2014). 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 (Lwasa et al. 2015; Revi et al.

2014). The new urban food systems may have diverse unexpected *adverse side-effects* with climates systems, such as lower efficiencies in food supply and higher costs than modern large-scale agriculture. The reduced food miles from the consumers and resource use efficiency have potentials benefits for emission reduction (Benis and Ferrão 2017). The benefits of Urban food forest that are intentionally planted woody perennial food producing species just like in agroforestry, are also cited for their carbon sequestration potentials (Kowalski et al. 2018).

There are trade-offs in urban food production systems reported for greenhouses used for production driven predominantly by external energy inputs, and in non-renewable resource depletion (Goldstein et al. 2016). 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 (Reidsma et al. 2010). Adding value to residues and side-streams may help some food supply chains to adapt to future markets with more stringent climate regulation and improve income of smallholder farmers. For example, coffee industry by-products can be further processed to yield value added products such as natural antioxidants, vitamins, enzymes, cellulose, starch, lipids, proteins and pigments of high significance to the food, pharmaceutical and cosmetic industries (Murthy and Madhava Naidu 2012). Production of value added products may also have positive impact when the overall efficiency of the food supply chain is increased. Negative impacts are expected when further processing of residues and coproducts lead to higher emissions or demand of resources in the food system.

6.3.2.8 Improved efficiency and sustainability of food processing, retail and agri-food industries

Improved efficiency and sustainability of retail and agri-food industries involve 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 efficiency and sustainability of retail and agri-food industries provides small benefits for climate mitigation (Chapter 2; Section 6.4; (Song et al.,2017) as GHG-friendly foods can create significant savings in agri-food GHG (Song et al. 2017) by reducing greenhouse gas emissions from transportation (Avetisyan et al. 2014), waste (Porter et al. 2016), and energy use (Mohammadi et al. 2014). In cases where climate extremes and natural disasters disrupt supply chain networks (Godfray et al. 2010), improved efficiency and sustainability of retail and agri-food industries can provide substantial benefits to climate adaptation by buffering the impacts of changing temperature and rainfall patterns on upstream agricultural production—yields and quality (Ridoutt et al.,2016). This response option can provide substantial benefits for food security by supporting healthier diets and reducing food loss and waste (Chapter 5; (Garnett et al. 2013). 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.

6.3.2.9 Increased energy efficiency in agriculture

Energy efficiency of agriculture can be improved to reduce the dependency on non-renewable energy sources. This can be realised either by deceased energy inputs, or through increased outputs per unit of input. Transformation of low carbon technologies such as renewable energy and energy efficiency can offer opportunities for significant climate change mitigation by providing a substitute to transport fuel (for example) that could benefit marginal agricultural resources (Gunatilake et al. 2014) while simultaneously contributing to long term economic growth (Begum et al. 2015). In poorer nations, increased energy efficiency in agricultural value added production in particular, can provide large mitigation benefits (Jebli et al. 2017). In some countries, managerial inefficiency (rather than 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 (Begum et al. 2015).

Improvements in carbon monitoring and calculation techniques such as the footprinting of agricultural products can enhance energy efficiency transition management and uptake in agricultural enterprises (Al-Mansour et al. 2017; (Baptista et al. 2013). Under certain scenarios, the efficiency of agricultural systems can stagnate and could exert pressure on grasslands and rangelands, thereby impacting land degradation and desertification (Vuuren et al.,2017). In some cases, organic farming systems have shown evidence of greater energy efficient than conventional counterparts. However, energy efficiency expressed per area unit generally increases with reducing tillage intensity (de Moraes Sá et al. 2017), or replacing chemical inputs by manures and manual weed control and does not always increase, since crop yields can be lower in organic and agroecology production systems (Alluvione et al., 2011; Reganold et al.,2016). The rebound effect can also result in adverse impacts when a reduction in energy use and emissions is less than the energy efficient improvement strategy.

6.3.2.10 Material substitution

Material substitution involves the use of wood products instead of fossil fuel-based building materials (e.g., concrete, iron, steel, aluminium, etc.). Such a substitution reduces carbon emissions both because the wood sequesters carbon during the growth phase and because it reduces the demand for fossil fuels (Smyth et al. 2014; Oliver et al. 2014; Eriksson et al. 2012; Sathre and O'Connor 2010), delivering a benefit for mitigation. No evidence was found of any impact upon adaptation, prevention of desertification or land degradation, or delivery of food security.

6.3.3 Integrated response options based on risk management

6.3.3.1 Establishing secure land tenure

Land tenure insecurity has been pointed to as a key driver of deforestation and land degradation in forested lands (Clover and Eriksen 2009; Damnyag et al. 2012; Finley-Brook 2007; Robinson et al. 2014; Stickler et al. 2017) and as a driver of lack of investment in agricultural lands (Rao et al. 2016; Holden and Otsuka 2014; Lawry et al. 2017\; Gebremedhin and Swinton 2003; Enki et al. 2001; Hajjar et al. 2012). Land tenure security can help strengthen local systems of common property management, which can make some communities more able to adapt to climate changes in the future (Gabay and Alam 2017; Dell'Angelo et al. 2017), and has also been shown to correlate with increases in food production (Maxwell and Wiebe 1998; Holden and Ghebru 2016; Corsi et al. 2017). Ensuring that communities and individuals, particularly poorer ones in developing countries, have secure and defendable land tenure rights over a variety of lands has been a policy supported by both national governments and international donors for many years. Establishing secure land tenure includes options such as: 1) formalisation through land titling and registration; 2) community co-management and decentralisation; and 3) legal and policy frameworks that recognise customary rights (Deininger and Feder 2009).

Land titling programs have been shown to lead to improved management of forests, including for carbon (Suzuki 2012; Balooni et al. 2008; Ceddia et al. 2015; Pacheco et al. 2012), primarily by providing legally secure mechanisms for exclusion of others (Nelson et al. 2001; Blackman et al. 2017), while evidence on effectiveness of land titling for other lands (such as agriculture or grazing) is less definitive (Jacoby and Minten 2007; Kerekes and Williamson 2010). Although secure land tenure tends to lead to improved management of forests with mitigation benefits (Nelson et al. 2002; Holland et al. 2017; Blackman et al. 2017), less is known about mitigation benefits from secure land titling in agriculture. Poor management of state and open-access lands, leading to tragedy of the commons situations, has been combatted in recent years by a move towards forest decentralisation and community co-management (with or without formal titling), which has shown considerable success in slowing forest loss and contributing to carbon mitigation (Agrawal et al. 2008; Chhatre and Agrawal 2009; Larson and

Pulhin 2012; Pagdee et al. 2006; Holland et al. 2017; Gabay and Alam 2017). Securing and recognising tenure for indigenous communities in particular (such as through revisions to legal or policy frameworks) has also been shown to be highly effective in reducing deforestation and improving land management, and is therefore also likely to help improve indigenous communities' ability to adapt to climate changes (Suzuki 2012; Balooni et al. 2008; Ceddia et al. 2015; Pacheco et al. 2012; Holland et al. 2017).

6.3.3.2 Prevention of land grabbing

Concerns about land grabbing have increased over the past decade, driven by a series of large-scale land acquisitions, and there are strong warnings that local food security may be threatened (Daniel 2011; Golay and Biglino 2013;Lavers 2012) while others see them as investments that can contribute to more efficient food production at larger scales (World Bank 2011; Deininger and Byerlee 2012). The scope of large-scale land acquisitions over the past years was around 45 million ha of land by 2010 (Borras et al. 2011), and around 200 million by 2018 (Land Matrix 2018). In Africa alone, nearly 500 land investment projects in 18 countries over nearly 40 million ha had been documented by 2015 (Balehegn 2015a). Because much of the land investments are driven by northern consumer demand, there is concern that southern smallholders (the site of most interventions) are being unduly impacted in inequitable ways, leading to impoverishment (Adnan 2013; Davis et al. 2014; Grant and Das 2015; Coscieme et al. 2016). However, there is inconclusive evidence that the food price crisis of 2008 was linked to expanding biofuel land deals (Kugelman and Levenstein 2013; Bush and Martiniello 2017).

Land grabs often contribute to increased tenure insecurity in surrounding lands, leading farmers to shift to cultivating smaller farms with less investments, potentially leading to food shortages (Aha and Ayitey 2017). A recent meta-analysis has shown that undernourished areas tend to export more "embodied agricultural lands" in foodstuffs for trade than they import (Marselis et al. 2017). Some scholars are concerned with displacement of smallholders from these grabs, potentially leading to impoverishment and increased (unsustainable) production elsewhere once pushed off lands (Borras Jr et al. 2011; Adnan 2013); these have happened with frequency in many countries in Africa, where communal land tenure authorities have allowed expropriation of locally used lands without other farmers' knowledge or compensation (Osinubi et al. 2016). Land grabbing can threaten not only agricultural lands of farmers, but also protected ecosystems, like forests and wetlands, particularly in countries with good land availability and poor accessibility (Hunsberger et al. 2017; Carter et al. 2017).

The primary mechanisms for combatting large scale land grabs have included restrictions on the size of land sales (Fairbairn 2015); pressure on agribusiness companies to agree to voluntary guidelines and principles for responsible investment (Collins 2014; Goetz 2013); attempts to repeal biofuels standards (Palmer 2014); and direct protests against the land acquisitions (Hall et al. 2015; Fameree 2016). Prevention of land grabbing can help strengthen local systems of common property management, which can make some communities more able to adapt to climate changes in the future (Gabay and Alam 2017; Dell'Angelo et al. 2017). Preventing land grabbling likely will help prevent some forms of degradation, as shifts from polyculture (often practiced by smallholders) to large scale monocrops in large scale land deals have negative consequences for soil degradation (Balehegn 2015a). Many of the large land investments intensify unsustainable lands uses, and rarely practice more sustainable forms of agriculture such as organic or low-till (Friis and Nielsen 2016). Preventing land grabbing will likely have positive impacts for biodiversity, because many large-scale acquisitions, particularly in African countries, exceed the documented cultivable land area for the country, thus many of these investments are likely expanding cultivation into forest, wetlands and grasslands (D'Odorico et al. 2017; Balehegn 2015a). Water demands for intensification of large scale investments are also likely to increase with impacts on other users of water (Lazarus 2014).

6.3.3.3 Management of urban sprawl

Unplanned urbanisation leading to sprawl and extensification of cities along the rural-urban fringe has been pointed to as a driver of agricultural land loss and a threat to food production around cities; for example, China has lost 3–5% of productive farmlands to industrial and urban development in recent years (Chen 2007; Cai et al. 2013), and the US is on a similar trajectory (Francis et al. 2012), while in India, more urban land is reclaimed from woodlands and grassland than from cropland (Gibson et al. 2015). This rapid urban expansion is especially strong in new emerging towns and cities (Lee et al. 2015). 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 (Tan et al. 2009; Qian et al. 2015). China in particular has a strict national Requisition–Compensation Balance of Farmland policy requiring balance in expropriations of farmland (Shen et al. 2017). Such policies promoting densification and less haphazard development are estimated to have the potential to save 62,000 km^2 of arable land by 2030 in India alone (Gibson et al. 2015). 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. 2013a).

6.3.3.4 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 at risk (Adger 1999). 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 (Ellis 2008; DiGiano and Racelis 2012). Livelihood diversification offers potentials for prevention and reversal of desertification and land degradation, particularly through non-traditional crops or trees in agroforestry systems which improve soil (Antwi-Agyei et al. 2014). Livelihood diversification may increase on-farm biodiversity due to these investments in more ecosystem-mimicking production systems, like agroforestry and polycultures.

Diversification is increasingly favoured by farmers as a low-cost and high benefit strategy (Ahmed and Stepp 2016a). Diversification combined with forms of credit and insurance can help households ride out short-term shocks and crises and allow them to have a broader range of options for the future (Thornton and Herrero 2014). However, there is unclear agreement in the literature as to how much diversification can be encouraged through policy, and the most effective ways to do so (Bryceson 1999;Rakodi 1999). Examples include market liberalisation; targeting of social safety nets and credit; provision of rural services like extension; extension of infrastructure (roads, access to markets) (Ellis 1998)(Barrett et al. 2001). There are also barriers to diversification, particularly for poorer households and female headed households, such as lack of assets to invest in new income streams, lack of education which inhibits proactive searches for new income sources, or discrimination (Berman et al. 2012; Ahmed and Stepp 2016a; Ngigi et al. 2017).

6.3.3.5 Promotion of seed sovereignty

Seed sovereignty refers to movements to retain control over "people's right to save, replant, breed and share seeds, and their right to participate in decision-making processes regarding rules and laws that regulate their access and use" (Wattnem 2016). Options for seed sovereignty include farmer seed networks and community seed banks; open source plant breeding and use of open pollinated seeds; declaration of GM-free zones; and educational programs (Kloppenberg 2010; Luby et al. 2015; Bowman 2015; Campbell and Veteto 2015; Reisman 2017; Patnaik et al. 2017). Seed sovereignty can potentially help address some of these issues of yield, particularly in the many parts of the developing world that do not rely on commercial seed inputs, through general promotion of local seed saving initiatives. Such actions can include seed networks, banks and exchanges, and non-commercial open source plant breeding (Kloppenberg 2010; Luby et al. 2015; Bowman 2015; Campbell and Veteto 2015; Reisman 2017; Patnaik et al. 2017). These locally developed seeds can both help protect local agrobiodiversity and can often be more climate resilient than generic commercial varieties (Coomes et al.,2015; van Niekerk and Wynberg 2017; Vasconcelos et al. 2013), although the impacts on food security and overall land degradation are inconclusive.

6.3.3.6 Early warning systems for disaster risk reduction

Early warning systems (EWS) to enable disaster risk reduction (DRR) can include options such as 1) education systems; 2) hazard and risk maps; 3) hydrological and meteorological monitoring (such as flood forecasting or extreme weather warnings); 4) and communications systems to pass on information to enable action (Bouwer et al. 2014; Cools et al. 2016). Combined with EWS, DRR approaches have long been considered to reduce the risk of household asset damage during one-off climate events (e.g., often used for response to floods and typhoons), and DRR approaches are increasingly being combined with climate adaptation policies (Thomalla et al. 2006; Mercer 2010). The Hyogo Plan of Action is a UN framework for nations to build resilience to disasters through effective integration of disaster risk considerations into sustainable development policies (Djalante et al. 2012; Sternberg and Batbuyan 2013). For example, in Vietnam a national strategy on disasters based on Hyogo has introduced the concept of a “four-on-the-spot” approach for DRR of: proactive prevention; timely response; quick and effective recovery; and sustainable development (Garschagen 2016).

The literature on effective EWS to reduce vulnerability and increase adaptive capacity has stressed that they must be ‘end-to-end,’ both reaching communities at risk and supporting and empowering vulnerable communities to take appropriate action (Ajibade and McBean 2014). The most effective EWSs are not simply technical systems of information dissemination, but utilise and develop community capacities, create local ownership of the system, and be based on a shared understanding of needs and purpose (Vogel and O’Brien 2006). Tapping into existing traditional or local knowledge has also been recommended for EWSs (Alessa et al. 2016).

6.3.3.7 Commercial crop insurance

Crop insurance is one of the most widely used risk-hedging financial vehicles to guard against yield losses in agriculture by providing reimbursements to farmers from actual or estimated losses (Havemenn and Muccione 2011; Meze-Hausken et al. 2009). Crop insurance 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 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 (Havemenn and Muccione 2011; Meze-Hausken et al. 2009). Crop insurance is also highly subsidised in much of the developed world (Smith and Glauber 2012).

One particularly new model is weather-indexed insurance, which allows for pay-outs when a weather parameter is surpassed (e.g., seasonal rainfall falls below threshold, or a storm ranks above a severity index) (Akter et al. 2016). Such insurance allows smallholders to reduce farming risks through fairly low-cost payments which are often highly subsidised by governments, as such programs have often failed to attract sufficient buyers or have remained financially unfeasible for commercial insurance sellers (Giné et al. 2008; Meze-Hausken et al. 2009). Peterson (2012) cautions that index insurance that relies too much on technical expertise has the potential to neglect local context in design and implementation. Gender differences have also been noted, with female farmers (who often comprise more than 50% of the rural workforce in many countries) exhibiting stronger loss aversion behaviour and less likely to purchase weather insurance (Akter et al. 2016). The overall impact of index insurance on food production supply and access also not been assessed.

Traditional crop insurance has generally been seen as positive for food security as it leads to expansions in agricultural production areas and increased food supply (Claassen et al. 2011; Goodwin et al. 2003).

However, while insurance can usefully provide ways for farmers to weather different risks in agricultural production, it may also 'mask' truly risky agriculture and prevent farmers from seeking less risky production strategies, such as diversification (Sanderson et al.,2013; Skees and Collier 2012; Jaworski 2016; Annan and Schlenker 2015). Insurance can also provide perverse incentives for farmers to bring additional lands into crop production, particularly marginal or risky lands and in high-yield short-return farming, leading to greater risk of degradation (Claassen et al. 2011; Goodwin and Smith 2003).

6.4 Potentials for addressing the land challenges

In this section, we assess how each of the integrated response options described in Section 6.3 address the land challenges of climate change mitigation (6.4.1), climate change adaptation (6.4.2), desertification (6.4.3), land degradation (6.4.4), and food security (section 6.4.5). The criteria for designating potential impacts either positive or negative, and as large, moderate, small or negligible, are summarised in Table 6.3.

Table 6.3 Key for criteria used to define size of 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 300 million hectares	Positively impacts more than around 300 million hectares	Positively impacts more than around 100 million people
Moderate positive	0.3 to 3 $GtCO_2$-eq	1 million to 25 million	50 to 300 million hectares	50 to 300 million hectares	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	50 to 300 million hectares	50 to 300 million hectares	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 300 million hectares	Negatively impacts more than around 300 million hectares	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 and Jiang 2014a). For adaptation, numbers are set relative to the about 5 million lives lost per year attributable to climate change and the 100 million lives predicted to be lost between 2010 and 2030 (DARA 2012) with the largest category representing 25% of this total. For desertification and land degradation, categories are set relative to the 1–6 billion hectares 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 about 800 million people currently undernourished (HLPE 2017) with the largest category representing around 12.5% of this total.

6.4.1 Potential of the integrated response options for delivering mitigation

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

6.4.1.1 *Integrative response options based on land management*

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

Table 6.4 Mitigation effects of response options based on land management

Integrative response option	Potential	Confidence	Citation
Increased soil organic matter content (and reduced losses)	3-5 GtCO2/yr	Robust evidence; high agreement	Smith (2016), Fuss et al. (2018)
Improved cropland management	~2.3 GtCO2e/yr	Robust evidence; medium agreement	Smith et al. 2008, 2014
Improved livestock management	0.2-1.8 GtCO2e/yr	Robust evidence; high agreement	Smith et al. 2008, 2014; Herrero et al. (2016)
Improved grazing land management	1.4-1.8 GtCO2.yr	Robust evidence; high agreement	Herrero et al. 2016; Conant et al. 2017; Smith et al. 2008, 2014
Increased food productivity	>13 GtCO2/yr	Robust evidence; high agreement	Burney et al. (2010)
Agro-forestry	0.7 Gt CO2/yr	Medium evidence; high agreement	Zomer et al. (2016)
Sustainable forest management and forest restoration	Up to 5.2-7 Gt CO2e/yr, of which 1.5 Gt CO2e/yr from forest management and 3.7 to 5.5 Gt CO2/yr from forest restoration	Robust evidence; medium agreement for forest management; Limited evidence; medium agreement for forest restoration	Griscom et al. 2017; Dooley and Kartha 2018
Agricultural diversification	> 0	medium evidence; medium agreement	Campbell et al. 2014; Cohn et al. 2017
Management of soil erosion	Source of 1.36-3.67 to sink of 0.44-3.67 Gt CO2/yr	Robust edivence; low agreement	Jacinthe & Lal, 2001, Lal et al., 2004; Stallard, 1998; Smith et al., 2001; Smith et al., 2005; van Oost et al., 2007
Prevent / reverse soil salinization	0 GtCO2/yr	Medium evidence; medium agreement	Wong et al. 2010; UNCTAD 2011; Dagar et al. 2016
Prevention of compaction	>0	Medium evidence; medium agreement	Chamen et al. 2015; Epron et al. 2016; Tullberg et al. 2018
Fire management	0.48-1.76 GtCO2/yr	Robust evidence; medium agreement	Tacconi 2016; Arora et al., 2018
Management of landslides and natural hazards	>0	Limited evidence; medium agreement	Noble et al. 2014
Ecosystem-based adaptation	23.8 Gt CO2e/yr	Robust evidence; medium agreement	Griscom et al. 2017
Reduced deforestation and degradation	Up to 3.6 Gt CO2e/yr	Robust evidence; high agreement	Griscom et al. 2017
Management of pollution including acidification	1) Reduce projected warming ~0.5 deg-C by 2050; 2) Reduce terrestrial C uptake 0.55-7.33 GtCO2/yr	1) Robust evidence; medium agreement; 2) Robust evidence; medium agreement	1)Shindell et al., 2012; 2) Bala et al., 2013
Management of invasive species / encroachment	No global estimates	No evidence	
Reforestation	See afforestation		
Restoration and avoided conversion of coastal wetlands	1.1 GtCO2/yr	Low evidence; high agreement	Griscom et al. (2017)
Biochar	Technical potential: 3.7-6.6 GtCO2e/yr; Feasible potential (carbon stabilisation only): 0.5-4.6 GtCO2e/yr from carbon stabilisation	Medium evidence; medium agreement	Woolf et al. (2010); Smith (2016), Fuss et al. (2018); IPCC SR1.5
Restoration and avoided conversion of peatlands	1.6 GtCO2/yr	Low evidence; high agreement	Griscom et al. (2017)
Afforestation	up to 10 GtCO2/yr (range 2.7 - 17.9)	Robust evidence; medium agreement	Kreidenweis et al. 2016; Griscom et al., 2017
Avoidance of conversion of grassland to cropland	0.4 Gt CO_2/yr	Low evidence; low agreement	Calculated from values in Poeplau et al. (2011) and Kruase et al. (2017)
Enhanced weathering of minerals	0.5-4 $GtCO_2$/yr	Low evidence; medium agreement	Lenton 2010; Smith et al. 2016a; Taylor et al. 2016; Beerling et al., 2018
Bioenergy and BECCS	up to 20 GtCO2e/yr	Robust evidence; high agreement	Chapter 2; IPCC SR1.5; Kriegler et al., 2017; Fuss et al. 2014

The global mitigation potential for increasing soil organic matter stocks in mineral soils is estimated to be in the region of 3–5 $GtCO_2$-eq yr^{-1} (Smith et al.(2008); Smith, 2016; Fuss et al.,2018; Table 6.4).

Improved cropland management could provide moderate levels of mitigation (about 2.3 $GtCO_2$-eq yr^{-1}; (Smith et al.,2008, 2014; Table 6.4). The technical potential is estimated by adding technical potentials for cropland management (about 1.4 $GtCO_2$-eq yr^{-1}), rice management (about 0.2 $GtCO_2$-eq yr^{-1}) and restoration of degraded land (about 0.7 $GtCO_2$-eq yr^{-1}) from Smith et al.(2008): Smith et al. 2014). Note that much of this potential arises from soil carbon sequestration so there is an overlap with that response option.

Potential of improved livestock management is also moderate (0.2–1.8 $GtCO_2$-eq yr^{-1}; Table 6.4); The lower value of the range for the technical potential is from (Smith et al.(2008) which included only direct livestock measures. The upper value for the range of the technical potential is from (Herrero et al.,2016) and includes also indirect effects, and some components of grazing land management, and soil carbon sequestration, so there is an overlap with these response options.

Grazing lands can store high carbon contents in soil and root biomass compartments (Conant and Paustian 2002; O'Mara; 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. Conant et al. (2005) caution that increases in soil carbon stocks could be offset by changes in N_2O fluxes.

Sustainable intensification to deliver increased food productivity could provide high levels of mitigation, with yield improvement estimated to have contributed to emissions savings of >13 $GtCO_2$ yr^{-1} since 1961 (Burney et al.,2010; Table 6.4). It also reduces the greenhouse gas intensity of products (Bennetzen et al.,2016a; Bennetzen et al. 2016) which means a smaller environmental footprint of production, since demand can be met using less land and/or with fewer animals.

(Zomer et al.(2017) reported that the trees in agroforestry landscapes has increased carbon stock by 2 GtC = 7.33 $GtCO_2$ between 2000–2010, which is equivalent to = 0.7 $GtCO_2$ yr^{-1}.

Improved management of natural forests could potentially contribute to large and cost-effective mitigation, equal to 1.5 Gt CO_2-eq yr^{-1} by 2030 (Griscom et al. 2017). In addition, forest restoration potentially leads to a cumulative potential carbon sequestration of 220–330 $GtCO_2$ in the 21st century (Dooley and Kartha 2018). More 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 improved forest management, expansion of forest areas, energy substitution, and establishment of forest reserves) in the European Union has the potential to contribute to an additional 0.4 Gt CO_2 yr^{-1} mitigation by 2050. Extending the lifetimes of wood products could potentially remove 36 $GtCO_2$ from the atmosphere between 2016 and 2100, globally (Houghton and Nassikas 2018;Mbow et al. 2014) suggest that agro-forestry systems have the potential to contribute to 0.5–3.1 Mg C ha^{-1} yr^{-1} of carbon sequestration in Africa.

Agricultural diversification mainly aims at increasing climate resilience, but its mitigation potential is only modest as a function of type of crop, fertiliser management, tillage system, and soil type (Campbell et al. 2014) Cohn et al. 2017).

The management and control of erosion may avoid 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 & Lal, 2001, Lal et al., 2004) to a sink of 0.44–3.67 $GtCO_2$ yr^{-1} (Stallard, 1998; Smith et al., 2001; Smith et al., 2005; van Ooost et al., 2007; Table 6.4), the overall impact of erosion control on mitigation is context specific and at the global level, uncertain (Hoffmann et al.,2013).

Salt-affected soils are highy constrained envirommengts that require permanent prevention of salinisation. Their mitigation potential is very modest (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 is not high. Global mitigation potential is very modest (Chamen et al.,2015; Epron et al.,2016; Tullberg et al.,2018).

For fire management, total emissions from the fires have been in the order of 1.75 $GtCO_2$ yr^{-1} (Tacconi 2016) 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 Gt CO_2 yr^{-1} for the 1960–2009 period. (Arora and Melton 2018; Table 6.4).

Management of landslides and natural hazards is a key climate adaptation option but its mitigation potential is very modest (Noble et al. 2015).

(Griscom et al. (2017) estimated the potential for all natural climate solutions, the majority of which are beased on ecosystem-based adaptation to be 23.8 Gt CO_2 yr^{-1}, comprised a number of the other response options (such as forest, peatland and wetland restoration) listed in this section.

Reducing deforestation and forest degradation rates represents one of the most effective options for climate change mitigation (Griscom et al. 2017). Furthermore, Houghton and Nassikas (2018) estimate that stopping deforestation and allowing secondary forests to grow would yield cumulative negative emissions between 2016 and 2100 of about 439 $GtCO_2$ between 2016 and 2100, globally.

In terms of management of pollution, including acidification, (Shindell et al.(2012) identified 14 measures targeting reduction in 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 N 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 N deposition ranges: from

0.55–1.28 $GtCO_2$ yr^{-1} (Vries et al.,2009; de Vries et al.,2008) (Zaehle et al.,2011) to 3.67–7.33 $GtCO_2$ yr^{-1} (Vries et al.,2009; de Vries et al.,2008; Holland et al. 1997; Magnani et al.,2007; Zaehle et al.,2011).

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

Coastal wetland restoration could provide moderate levels of climate mitigation, with avoided coastal wetland impacts and coastal wetland restoration estimated to deliver 0.3 and 0.8 (total 1.1) $GtCO_2$ yr^{-1}, respectively, by 2030 (Griscom et al. 2017).

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 $GtCO_2$-eq yr^{-1} (including 2.6–4.6 $GtCO_2$-eq yr^{-1} carbon stabilisation; Table 6.4), with theoretical potential to reduce total emissions over the course of the century by 240 – 475 $GtCO_2$-eq (Woolf et al.,2010). (Fuss et al.,(2018) propose a range of 0.5–2 $GtCO_2$-eq yr^{-1} as the sustainable potential for negative emissions through biochar, similar to the range proposed by (Smith 2016) IPCC SR1.5.

Peatland restoration could provide moderate levels of climate mitigation, with avoided peat impacts and peat restoration estimated to deliver 0.8 and 0.8 (total 1.6) $GtCO_2$ yr^{-1}, respectively, by 2030 Griscom et al. 2017), though there could be a temporary increase in methane emissions after restoration (Jauhiainen et al. 2008; Table 6.4).

Afforestation and reforestation have a global mitigation potential estimated at about 10 $GtCO_2$ yr^{-1} (Griscom et al., 2017; Kreidenweis et al., 2016), of which about 2 $GtCO_2$ yr^{-1} is from afforestation in temperate climates and 8 $GtCO_2$ yr^{-1} is in tropical and subtropical climate, with a 95% confidence interval (estimated with the Delphi method) between 2.7 and 17.9 $GtCO_2$ yr^{-1} (Griscom et al., 2017; Table 6.4). Climate change mitigation benefits of afforestation are reduced at high latitudes owing to the surface albedo feedback.

Avoidance of 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 a starting soil organic carbon stock of grasslands of 115 t C ha^{-1} (POEPLAU et al. 2011), this is equivalent to a loss of 41.5 t C ha^{-1} on conversion to cropland. Mean annual global cropland conversion rates (1961–2003) have been around 4.7 Mha yr^{-1} (Krause et al. 2017), or 94 Mha over a 20 year period. The equivalent loss of soil organic carbon over 20 years would therefore be 3.9 Gt C, or 14 Gt CO_2-eq = 0.7 Gt CO_2 yr^{-1} (Table 6.4).

Enhanced mineral weathering provides substantial climate mitigation, with a global mitigation potential in the region of about 0.5–4 $GtCO_2$ yr^{-1} (Beerling et al. 2018 ;Lenton 2010; Smith et al. 2016a; Taylor et al. 2016; Table 6.4).

Scenarios using BECCS show large sequestration potential (IPCC SR1.5; Chapter 2; Table 6.4); however, these estimates exclude N_2O associated with fertiliser application and land-use change emissions.

6.4.1.2 Integrative response options based value chain management

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

Table 6.5 Mitigation effects of response options based on value chain managment

Integrative response option	Potential	Confidence	Citation
Dietary change	1.8 to 5 GtCO2/yr	Robust evidence; high agreement	Stehfest et al. 2009, Bajželj et al. 2014, Tilman and Clark, 2014; Popp et al. 2010
Reduced post-harvest losses	5 $GtCO_2$/yr	Medium evidence; medium agreement	Bajželj et al. 2014
Reduced food waste (consumer or retailer)	5 $GtCO_2$/yr	Medium evidence; medium agreement	Bajželj et al. 2014
Promotion of value-added products	No global estimates	No evidence	
Stability of food supply	No global estimates	No evidence	
Improved food transport and distribution	0.37 GtCO2/yr	Medium evidence; medium agreement	James & James, 2010; Vermeulen et al., 2012
Urban food systems	No global estimates	No evidence	
Improved efficiency and sustainability of food processing, retail and agri-food industries	See improved energy efficency		
Increased energy efficiency in agriculture	0.37 GtCO2/yr	Medium evidence; medium agreement	James & James, 2010; Vermeulen et al., 2012
Material substitution	0.9 GtCO2/yr	Low evidence; medium agreement	Gustavson (2006)

Dietary change and waste reduction can provide large co-benefits for mitigation, with potentials of up to 5 $GtCO_2$ per year for both (Bajželj et al. 2014; Stehfest et al. 2009; Tilman and Clark 2014; Aleksandrowicz et al. 2016; Table 6.5). Estimates for food waste reduction include both consumer / retailed waste and post-harvest losses.

There are no estimates of the mitigation potential for promotion of value-added products nor for urban food systems. There is no quantified evidence linking mitigation benefits to stabilising food prices and supply.

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.2012). 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 and sustainability of food processing, retail and agri-food industries, and improved energy efficiency; Table 6.5).

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, for example, about 1 $GtCO_2$ yr^{-1} (Gustavsson et al. 2006; Table 6.5). Most studies quantify the amount of mitigation per m^3 of wood used (Sathre and O'Connor 2010) and not a global potential.

6.4.1.3 Integrative response options based on risk management

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

Table 6.6 Mitigation effects of response options based on risk management

Integrative response option	Potential	Confidence	Citation
Establishing secure land tenure	0.96 GtCO2/yr	Low evidence; high agreement	Frechette et al. 2018
Prevention of land grabbing	0.09 GtCO2/yr	Low evidence; low agreement	Romijn 2011
Management of urban sprawl	No global estimates	No evidence	
Livelihood diversification	No global estimates	No evidence	
Promotion of seed sovereignty	No global estimates	No evidence	
Early warning systems for disaster risk reduction	None likely	No evidence	
Commercial crop insurance	<0.024 GtCO2e/yr	Low evidence; medium agreement	EPA 2018; Claussen et al 2011

Indigenous Peoples and Local Communities, who tend to have the least secure tenure rights, have control of forestlands storing approximately 263 Mt carbon (equivalent to 964 $MtCO_2$; Frechette et al. 2018). It is unclear however how much of this is at risk without secure land tenure policies.

Estimates of carbon emissions from conversion of Miombo woodland (often done with land grabbing) in east Africa for Jatropha for biofuels can give a low-end estimate of overall mitigation impact. Several million hectares of miombo have been targeted for Jatropha development (https://landmatrix.org/en/get-the-detail/), and the estimated carbon debt from conversion is 24.5 tC ha^{-1} (89.8 tCO_2 ha^{-1}) over 20 years.

Extensive and less dense urban developments tend 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 US 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 be likely to 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 (not quantified, however). There is no literature on any mitigation impact from Early Warning Systems.

Cropping insurance may in fact lead to carbon losses as there is evidence that subsidised crop insurance programmes can induce producers to bring additional land into crop production, particularly marginal or risky lands that may be more environmentally sensitive (Claassen et al. 2011). Policies to deny crop insurance to farmers who have converted grasslands in the US resulted in a 9% drop in conversion, which likely has positive mitigation impacts (Claassen et al. 2011). Estimates of emissions from cropland conversion in the US in 2016 were 23.8 Mt CO_2-eq, only some of which could be attributed to insurance as a driver.

6.4.2 Potential of the integrated response options for delivering adaptation

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

6.4.2.1 Integrative response options based on land management

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

Table 6.7 Adaptation effects of response options based on land management

Integrative response option	Potential	Confidence	Citation
Increased soil organic matter content (and reduced losses)	Up to 3200 million people	Low evidence; high agreement	IPBES (2018)
Improved cropland management	>25 million people	Robust evidence; high agreement	Vermeulen et al. 2012; Challinor et al. 2014; Lipper et al. 2014; Lobell 2014
Improved livestock management	1-25 million people	Robust evidence; high agreement	Porter et al. 2014; Rojas-Downing et al. 2017
Improved grazing land management	1-25 million people	Robust evidence; high agreement	Porter et al. 2014
Increased food productivity	>160 million people	Low evidence; high agreement	Pretty et al. (2018)
Agro-forestry	2300 million people	Medium evidence; high agreement	Lasco et al. (2014)
Sustainable forest management and forest restoration	No global estimates	Limited evidence; high agreement	Smith et al. 2014
Agricultural diversification	>25 million people	Robust evidence; high agreement	Vermeulen et al. 2012; Campbell et al. 2014; Cohn et al. 2017
Management of soil erosion	Up to 3200 million people	Low evidence; high agreement	IPBES (2018)
Prevent / reverse soil salinization	1-25 million people	Medium evidence; high agreement	Qadir et al. 2011; UNCTAD 2011; Dagar et al. 2016
Prevention of compaction	<1 million people	Medium evidence; medium agreement	Tim Chamen et al. 2015; Epron et al. 2016; Tullberg et al. 2018
Fire management	> 5.8 million people affected by wildfire; max. 0.5 million deaths per year by smoke	Robust evidence; medium agreement	Doerr and Santin, 2016; Johnston et al., 2012; Shannon et al., 2016
Management of landslides and natural hazards	>25 million people	Robust evidence; high agreement	Noble et al. 2014; Arnaez et al. 2015; Gariano and Guzzetti 2016
Ecosystem-based adaptation	2800 million people	Medium evidence; medium agreement	Bailis et al. (2015); Griscom et al. (2017)
Reduced deforestation and degradation	No global estimates	Limited evidence; high agreement	Karjalainen et al. 2010
Management of pollution including acidification	Prevent 0.5–4.7 million annual premature deaths globally	Robust evidence; high agreement	Anenberg et al., 2012; Shindell et al., 2012; West et al., 2013
Management of invasive species / encroachment	No global estimates	No evidence	
Reforestation	See afforestation		
Restoration and avoided conversion of coastal wetlands	up to 93-310 million people	Low evidence; low agreement	
Biochar	No global estimates	No evidence	
Restoration and avoided conversion of peatlands	No global estimates	No evidence	
Afforestation	> 25 million people	Low evidence; high agreement	Griscom et al, 2017; Smith and Boustamante, 2014; Sonntage et al., 2016
Avoidance of conversion of grassland to cropland	No global estimates	No evidence	
Enhanced weathering of minerals	No global estimates	No evidence	
Bioenergy and BECCS	Potentially large negative consequences	Low evidence; low agreement	

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 6.4.4.1), and restoring degraded land helps to improve resilience to climate change, soil carbon increase is an important option for climate change adaptation. With around 12 Mha 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 6.7).

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: (1) 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 (2) 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. 2012; Challinor et al.; Lipper et al. 2014; Lobell,2014). In the same way, improved livestock management is another technological adaptation option potentially affecting 1–25 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) .

Practices, such as sustainable intensification, that improve farm incomes allow households to build assets for use in times of stress, which thereby improves resilience (Campbell et al. 2014). By reducing pressure on land and increasing food production, increased food productivity could be beneficial for adaptation (Chapter 2; Section 6.4; Campbell et al. 2014). (Pretty et al.,2018) report that 163 million farms occupying 453 Mha have passed a resign threshold for application of sustainable intensification, suggesting the minimum number of people benefiting from increased productivity and adaptation benefits under sustainable intensification is >160 million, but with the total likely to be far higher (Table 6.7).

Around 30% of the world's rural population use trees in 46% of all agricultural landscapes (Lasco et al., 2014), meaning that 2.3 billion people benefit from agroforestry globally (Table 6.7).

Sustainable forest management and forest restoration positively impact adaptation through limiting the negative effects associated with pollution (of air and fresh water), infections and other diseases, exposure to extreme wheatear events and natural disasters, and poverty (e.g., Smith et al., 2014). Considering this complexity, there is no robust estimate available at global scale referring to the number of people (positively or negatively) affected by sustainable forest management and forest restoration potentially delivering adaptation.

Agricultural diversification is key to achieve climatic resilience (Campbell et al. 2014) Cohn et al. 2017). Crop diversification is one important adaptation option to progressive climate change (Vermeulen et al. 2012) 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).

Using figures from (FAO et al., 2015) , IPBES (2018) estimates that land losses due to erosion are equivalent to 150 Mha of land from crop production to 2050, or 4.5 million ha yr^{-1} (Foley et al.,2011). Control of soil erosion (water and wind) could benefit 1.1 billion ha of degraded land (Lal, 2004), 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 makes soil less vulnerable to loss under climate extremes, thereby increasing resilience to climate change (Garbrecht et al. 2015). 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 number of people benefiting from improved resilience to climate change has not been reported in the literature.

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

For fire management, Doerr et al.(2016) showed the number of people killed by wildfire was 1,940, and the total number of people affected was 5.8 million, with economic costs of >52,000 million USD globally. Johnston et al. (2012) showed 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 in 100,300 excess deaths across Indonesia, Malaysia and Singapore (Table 6.7).

Management of landslides and natural hazards are usually listed among planned adaptation options in mountainous, sloped hilly areas where non controlled runoff and avalanches may cause climatic disasters affecting million people from both urban and rural areas. Landslide control require both engineering and revegetation practices.

Ecosystem-based adaptation could benefit many millions of people. For example, 2800 million people are affected globally by unsustainable forest harvest for woodfuel (with the majority in Africa; (Bailis et al.2015), and these people would benefit from replacement of this woodfuel use under EbA (Griscom et al. 2017b).

Although there is *high agreement* on the fact that reduced deforestation and forest degradation positively impact adaptation and resilience of coupled human-natural systems, there are no global estimates on this impact. However, 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 limit the infectious diseases such as e.g. malaria in Africa, Asia, and Latin America, thus lowering the expenses associated to 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 of and 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). Reduced deforestation and forest degradation in arid and semiarid places, particularly in Africa, may improve the adaptation of about 1.5 billion people (UNESCO 2012).

For management of pollution, including acidification, (Anenberg et al.(2012) estimated that, for PM2.5 and ozone, respectively, fully implementing the 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. Shindell et al. (2012) considered ~400 emission control measures to reduce ozone and black carbon (BC), estimated to avoid 0.7 to 4.7 million annual premature deaths from outdoor air pollution. (West et al.,2013) estimated the 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.

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 150 Mha 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 population that could avoid these impacts through restoration of coastal wetlands has not been quantified, but this sets an upper limit.

Biochar has 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 (Chapter 2; Section 6.4; Woolf et al. 2010; Sohi,2012). 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 6.7).

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.

Afforestation and reforestation are important climate change adaptation response options (Ellison et al., 2017; Locatelli et al., 2015), andcan potentially help a large size of population to adapt to a changing climate (for example, trees general mitigate summer mean warming and temperature extremes (Findell et al., 2017; Sonntag et al., 2016; Table 6.7).

Avoidance of conversion of grassland to cropland might be some 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. There is no literature describing the global impacts of avoidance of conversion of grassland to cropland on adaptation.

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

Bioenergy and BECCS can require substantial amounts of cropland (Popp et al. 2017; Calvin et al. 2014a; Smith et al. 2016a) and water (Chaturvedi et al. 2013; Smith et al. 2016; Fuss et al. 2018; Popp et al. 2011; Hejazi et al. 2015b) suggesting that bioenergy and BECCS will have adverse side-effects for adaptation. However, no studies were found that quantify the magnitude of the side-effect.

6.4.2.2 Integrative response options based value chain management

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

Table 6.8 Adaptation effects of response options based on value chain management

Integrative 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 evidence; medium agreement	Kummu et al. (2012)
Reduced food waste (consumer or retailer)	No global estimates	No evidence	Muller et al. (2017)
Promotion of value-added products	500 million people	Low evidence; medium agreement	World Bank (2017)
Stability of food supply	>100 million	Medium evidence; medium agreement	Vermeulen et al (2012); Campbell et al. (2016); Timmer (2010); Ivanic &
Improved food transport and distribution	No global estimates	No evidence	
Urban food systems	No global estimates	No evidence	
Improved efficiency and sustainability of food processing, retail and agri-food industries	500 million people	Low evidence; low agreement	World Bank (2017)
Increased energy efficiency in agriculture	760 million	Low evidence; low agreement	World Bank (2017)
Material substitution	No global estimates	No evidence	

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

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 about12–15% 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), the reducing food waste could benefit 320–400 million people (12–15% of the 2681 million people affected by water stress / shortage).

It is estimated that 500 million smallholder farmers depend on agricultural businesses in developing countries, meaning that promotion of value-added products and improved efficiency and sustainability of food processing, retail and agri-food industries could potentially help up to 500 million people to adapt to climate change.

Consumers in lower income countries are most effected by price volatility, with sub-Saharan Africa and South Asia at highest risk (Regmi and Meade 2013; Fujimori et al.,2018). However, understanding of the stability of food supply is one of the weakest links in global food system research (Wheeler et al.,2013) as instability is driven by a confluence of factors (Headey and Fan 2008). Food price spikes in 2007 increased the number of people under the poverty line by between 100 million people (Ivanic and Martin 2008) to 450 million people (Brinkman et al.,2010), 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 reduced staple food price increased for 2 billion people (Timmer,2010). 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). One example of reduction in staple food price costs to consumers in Bangladesh from food stability policies saved rural households $887 million total (Torlesse et al.,2003). Food supply stability 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 that could benefit.

Given that 65% (0.76 billion) of poor working adults make a living through agriculture, increased energy efficiency in agriculture could benefit this 760 million people.

No studies were found linking material substitution to adaptation.

6.4.2.3 Integrative response options based on risk management

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

Table 6.9 Adaptation effects of response options based on risk management

Integrative response option	Potential	Confidence	Citation
Establishing secure land tenure	>100 million (up to 370 million ?)	Low evidence; high agreement	Garnett et al 2018
Prevention of land grabbing	No global estimates	No evidence	
Management of urban sprawl	Unquantified but likely to be many millions	Medium evidence; high agreement	Stone et al. 2010
Livelihood diversification	>100 million likely	Medium evidence; medium agreement	Morton 2007; Rigg 2006
Promotion of seed sovereignty	<100 million, but greater than 1 million	Low evidence; medium agreement	(Louwaars 2002; Santilit 2012
Early warning systems for disaster risk reduction	>100 million	High evidence; high agreement	Hillbruner and Moloney 2012
Commercial crop insurance	>1 million	Low evidence; low agreement	Platteau et al 2017

Approximately 370 million Indigenous peoples control around 38 million hectares of land, and many do not have secure formally recognised land tenure rights (Garnett et al.,2018). Improving tenure rights for these people and lands, in addition to undoubtedly more non-Indigenous peoples and lands facing tenure insecurity, would presumably have adaptation benefits, but these are unclear and unquantified in the literature.

Reports suggest that recent land grabbing has affected 12 million people globally in terms of declines in welfare (Adnan 2013; Davis et al. 2014). However, it is not known how many people would be able to be assisted in adaptation due to prevention of land grabbing as it has not been quantified in the literature.

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 effect 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 be then 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 over 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.

Seed sovereignty facilitates adaptation for many smallholders, given that from 60 to 100% of seeds used in some countries of the global South are local farmer-bred (non-commercial) seed (Louwaars 2002;), and moving to use of commercial seed would increase costs considerably for these farmers (Howard 2015). Seed networks and banks protect local agrobiodiversity and landraces, which are important to facilitate adaptation, and can provide crucial lifelines when crop harvests fail (Coomes et al. 2015; van Niekerk and Wynberg 2017; Vasconcelos et al. 2013); for example, problems of seed scarcity and dependence on outside supplies can be overcome by local control over seeds (Reisman 2017).

EWS are most useful for adaptation; for example, the Famine Early Warning System funded by the USAID has operated across 3 continents since the 1980s, and is praised for the timeliness, quantity, and quality of the warnings provided to countries, focusing on assessing agricultural changes due to climate/weather events, staple food prices, and health (Hillbruner and Moloney 2012). Many millions of people across 34 countries have access to early information drought and such information can assist communities and households in adapting to onset conditions. However, concerns have been raised as to how many people are actually reached by such systems; for example, less than 50% of respondents in Bangladesh had heard a cyclone warning before it hit, even though an EWS existed (Mahmud and Prowse 2012). Further, there are concerns that current EWS 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. 2015a), leading to less adaptation potential realised.

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 et al.,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 US 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 less than 30% of smallholders take out any form of insurance), but it is likely in the millions.

6.4.3 Potential of the integrated response options for addressing desertification

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

6.4.3.1 Integrative response options based on land management

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

Table 6.10 Effects on desertification of response options based on land management

Integrative response option	Potential	Confidence	Citation
Increased soil organic matter content (and reduced losses)	Up to 1137 Mha	Low evidence; high agreement	Lal (2001)
Improved cropland management	1000 Mha	Robust evidence, high agreement	Schwilch et al. 2014
Improved livestock management	50-300 Mha	Robust evidence, high agreement	Miao et al. 2015; Squires and Karami 2015
Improved grazing land management	50-300 Mha	Robust evidence, high agreement	Schwilch et al. 2014
Increased food productivity	1111-1514 Mha	Low evidence; high agreement	Burney et al. (2010)
Agro-forestry	1000 Mha (with >10% tree cover)	Medium evidence; medium agreement	Garrity (2012)
Sustainable forest management and forest restoration	No global estmates	No evidence	
Agricultural diversification	50-300 Mha	Medium evidence; medium agreement	Lambin and Meyfroidt 2011; Schwilch et al. 2014
Management of soil erosion	Up to 1137 Mha	Limited evidence; high agreement	Lal (2001)
Prevent / reverse soil salinization	1000 Mha	Robust evidence, high agreement	Qadir et al. 2013; FAO 2016
Prevention of compaction	1000 Mha	Robust evidence, high agreement	Hamza and Anderson 2005; FAO and ITPS 2015
Fire management	Up to 350-490 Mha/yr	Robust evidence; medium agreement	Arora and Melton 2018; Randerson et al. 2012; Tansey et al. 2004
Management of landslides and natural hazards	>0	Limited evidence; medium agreement	Noble et al. 2014; Djeddaoui et al. 2017
Ecosystem-based adaptation	>0	Limited evidence; low agreement	
Reduced deforestation and degradation	No global estimates	No evidence	
Management of pollution including acidification	~103 Mha	Robust evidence; low confidence	Oldeman et al. 1991
Management of invasive species / encroachment	No global estimates	No evidence	
Reforestation	See afforestation		
Restoration and avoided conversion of coastal wetlands	No global estimates	No evidence	
Biochar	No global estimates	No evidence	
Restoration and avoided conversion of peatlands	No impact		
Afforestation	200-2580 Mha	Medium evidence; high agreement	Kreidenweis et al. 2016; Griscom et al., 2017; Popp et al., 2017
Avoidance of conversion of grassland to cropland	up to 1.74 Mha/yr	Low evidence; low agreement	Foley et al. (2011)
Enhanced weathering of minerals	No global estimates	No evidence	
Bioenergy and BECCS	Negative impact on up to 300 Mha	Medium evidence; high agreement	Clarke et al., 2014; Popp et al., 2017; Smith et al., 2016

With over 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 1137 Mha of desertified soils (Lal 2001; Table 6.10).

Improved cropland, livestock and grazing land management are strategic options aiming at prevention of desertification, and may include from crop or animal type selection, stocking rates, tillage and/or cover crops, to land use shifting from cropland to rangeland, in general looking for increases in ground coverage by vegetation and protection against wind erosion (Schwilch et al. 2014; Bestelmeyer et al. 2015). Considering the three land uses and the extensive distribution of deserts and desertified lands globally, more than 1000 hectares could benefit from improved management techniques.

Burney et al. (2010) estimated that an additional global cropland area of 1111–1514 Mha would have been needed if productivity had not increased between 1961 and 2000. Given that agricultural expansion is a main driver of desertification (FAO et al. 2015), increased food productivity has prevented up to 1111–1514 Mha from exploitation and desertification (Table 6.10).

Agroforestry can help stabilise soils to prevent desertification (Section 6.3.1.6), so given that there are is around 1000 Mha of land with >10% tree cover, agroforestry could benefit up to 1000 Mha of land.

There is no availability of global studies about the future potential impact of forest management to reverse/halt desertification rates (in terms of area impacted). Most of the available literature sources are based on regional historical trends. 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).

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). All these practices can be related to improved crop management options and aim at increasing ground coverage by vegetation and controlling wind erosion losses.

Control of soil erosion could have large benefits for desertification control. Using figures from (FAO et al. 2015) IPBES (2018) estimates that land losses due to erosion to 2050 are equivalent to 150 Mha of land from crop production, or 4.5 Mha yr^{-1} (Foley et al.,2011), so soil erosion control could benefit up to 150 Mha of land in the coming decades. Lal (2001) estimates that desertification control (using soil erosion control as one intervention) could benefit 1137 Mha of desertified land globally (Table 6.10).

Salt-affected soils caused by human and climatic factors covers almost 1000 million hectares in the globe and is closely related to desertification. Its prevention encompasses judicious use of irrigation water and precision irrigation techniques, and groundwater management to alternate land use practices such as raising forest plantations, horticulture, agroforestry, high value medicinal, aromatic and flowering crops (Singh 2009; D'Odorico et al. 2013).

In degraded arid grasslands, shrublands and rangelands, desertification can be reversed by soil compaction alleviation by installation of enclosures and removal of domestic livestock (Allington et al. 2010).

For fire management, Arora and Melton (2018) estimated burned area from model and GFED4.1s0 over 1997–2014 period was 483.4 and 485.5 Mha yr^{-1}. Randerson et al. (2012) estimated small fires increased total burned area globally by 35% from 345 to 464 Mha yr^{-1}. (Tansey et al. 2004) estimated over 350 Mha of burned areas were detected in the year 2000. Neary et al.,(2009) noted that wildland fire is now driving desertification in some of the forests in the western USA, the Mediterranean area, and Australia. From 2004 to 2007, the USA had wildland fires that burned about 3.3–3.8 Mha yr^{-1}. Portugal suffered the worst and second worst wildland fire from 2003 to 2005. In 2005, 338,262 ha of forest land burned in Portugal (Table 6.10).

Although slope and slope aspect are predictive factors of desertification occurrence, most influencing 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 desertification occurrence.

There are no estimates on the potential global impact of ecosystem-based adaptation on desertification control, though the impact would be expected to be positive where applied.

There is no availability of global studies on the potential impact of reducing deforestation and forest degradation on desertification rates (in terms of area impacted). At local level, in Thailand it was found that the desertification risk reduces when the land use is changed from bare lands to agricultural lands and forests, and from denuded forests to forests; conversely, the desertification risk increases when converting forests and denuded forests to bare lands (Wijitkosum, 2016).

The global extent of chemical soil degradation (salinisation, pollution, and acidification) is about 103 Mha (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.

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

There are likely 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 global extent of chemical soil degradation with 77 Mha affected by salinisation, 21 Mha affected by pollution, and 6 Mha affected by pollution (total: 103 Mha), so this is the area that could potentially benefit from pollution management measures.

Afforestation and reforestation 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 (Nasiru Idris 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 (Feng et al. 2016; Yang et al.). Afforestation and reforestation programs can be deployed over large areas of the Earth, so to create synergies in areas prone to desertification. Global estimates of land potentially available for afforestation are up to 2580 Mha 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 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 amount of area available declines to about 680 Mha (95% confidence interval of 230 and 1125 Mha), of which about 472 Mha in the tropics and 206 in temperate regions (Griscom et al., 2017; Table 6.10).

Since shifting from grassland to tilled crops increases erosion and soil loss, there are significant benefits for prevention or reversal of desertification, by stabilising soils in arid areas (Chapter 3). Cropland expansion during 1985 to 2005 was 35.89 Mha, or 1.74 Mha yr^{-1} (Foley et al.,2011). Since not all of this expansion will be from grasslands or in desertified areas, the maximum contribution of prevention of conversion of grasslands to croplands is therefore 1.74 Mha yr^{-1}, a small global benefit for desertification control (Table 6.10).

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. 2016b; Clarke and Jiang 2014a; Popp et al. 2017), with as much as 1500 Mha in 2100 in 2°C scenarios (Popp et al. 2017), increasing pressures for desertification (Table 6.10).

6.4.3.2 Integrative response options based on value chain management

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

Table 6.11 Effects on desertification of response options based on value chain management

Integrative response option	Potential	Confidence	Citation
Dietary change	80-240 Mha	Medium evidence; medium agreement	Bajželj et al. 2014; Stehfest et al. 2009; Tilman and Clark 2014
Reduced post-harvest losses	<198 Mha/yr	Robust evidence; medium agreement	Kummu et al. 2012
Reduced food waste (consumer or retailer)	140 Mha	Low evidence; medium agreement	Bajželj et al. 2014
Promotion of value-added products	No global estimates	No evidence	
Stability of food supply	No global estimates	No evidence	
Improved food transport and distribution	No global estimates	No evidence	
Urban food systems	No global estimates	No evidence	
Improved efficiency and sustainability of food processing, retail and agri-food industries	No global estimates	No evidence	
Increased energy efficiency in agriculture	No global estimates	No evidence	
Material substitution	No global estimates	No evidence	

Dietary change and waste reduction both result in decreased cropland and pasture extent (Bajželj et al. 2014a; Stehfest et al. 2009; Tilman and Clark 2014a), reducing the pressure for desertification (Table 6.11).

Reduced post-harvest losses could spare 198 Mha of cropland globally (Kummu et al.,2012). Not all of this land could be subject to desertification pressure, so this represents that maximum area that could could be relieved from desertification pressure by reduction of post-harvest losses.

There are no global estimates of the impact on desertification of promotion of value-added products, improved food transport and distribution, urban food systems, improved efficiency and sustainability of food processing, retail and agri-food industries or increased energy efficiency in agriculture. There are no studies looking at the impact of food price instability or stabilisation policies on desertification. No studies were found linking material substitution to desertification.

6.4.3.3 Integrative response options based on risk management

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

Table 6.12 Effects on desertification of response options based on risk management

Integrative response option	Potential	Confidence	Citation
Establishing secure land tenure	No global estimates	Low evidence; low agreement	Galvin 2009
Prevention of land grabbing	Probably less than 1 Mha	Low confidence; low evidence	
Management of urban sprawl	>0.5 Mha	Low evidence; high agreement	Barbero- Sierra et al. 2013
Livelihood diversification	No global estimates	Low evidence; low agreement	Hermann & Hutchinson 2005
Promotion of seed sovereignty	No global estimates	No evidence	
Early warning systems for disaster risk reduction	No global estimates	Low evidence; medium agreement	Pozzi et al. 2013
Commercial crop insurance	Likely negative impacts but not quantified	Low evidence; medium agreement	Claassen et al. 2011

Anecdotal evidence suggests that many pastoralists in lands at risk from desertification do not have secure land tenure, but there is mixed evidence if securing pastoral lands reduces desertification risks (Ite 1998;Galvin 2009).

At least 45 Mha, and as many as 82 Mha, of large scale land acquisitions have occurred between 2005-2015 (Borras et al. 2011;Rulli et al. 2013; Balehegn 2015), but it is unknown how much of this land is at risk of desertification; probably only small numbers since drylands (with the exception of Jatropha) have not been targeted for land acquisitions, and land acquisitions have been low in areas of the Middle East/North Africa most at risk of desertification (Ambalam 2013; Rulli et al. 2013). In some places land acquisitions have been promoted as a way to prevent desertification, by increasing vegetation cover (Boamah 2014).

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 impacts in terms of prevention and reversal of desertification when the diversification involves expanding into tree crops that may reduce the need for tillage (Antwi-Agyei et al. 2014). In Tibet, pastoralist households will little opportunity for diversification tend to overgraze, leading to desertification (Zhang et al. 2008). Many anti-desertification programs call for diversification (Stringer et al., 2009), but there is little evidence for how many households had done so (Herrmann et al., 2005). However, there are no quantified numbers for global impacts.

The literature is unclear on if seed sovereignty has any relationship to desertification, although some local seeds are likely more adapted to arid climates and less likely to degrade land than commercial introduced varieties (Mousseau 2015). Some anti-desertification programs have also shown more success using local seed varieties (Bassoum et al., 2014; Nunes et al., 2016).

Some EWS 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, 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 these EWS.

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 US Midwest (Claassen et al. 2011), a loss of several hundred thousand ha.

6.4.4 Potential of the integrated response options for addressing land degradation

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

6.4.4.1 Integrative response options based on land management

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

Table 6.13 Effects on land degradation of response options based on land management

Integrative response option	Potential	Confidence	Citation
Increased soil organic matter content (and reduced losses)	1100 Mha	Medium evidence; high agreement	Lal (2004)
Improved cropland management	1000 Mha	Robust evidence, high agreement	Lal 2015; Smith et al. 2016
Improved livestock management	1000 Mha	Robust evidence, high agreement	Lal 2015; Smith et al. 2016
Improved grazing land management	1000 Mha	Robust evidence, high agreement	Smith et al. 2016
Increased food productivity	1111-1514 Mha	Low evidence; high agreement	Burney et al. (2010)
Agro-forestry	1000 Mha land (with >10% tree cover)	Medium evidence; medium agreement	Garrity (2012)
Sustainable forest management and forest restoration	Up to 400 Mha by 2050 (net increase in tree cover) for forest restoration	Limited evidence; high agreement	Wolff et al. 2018
Agricultural diversification	100-500 Mha	Medium evidence; medium agreement	Lambin and Meyfroidt 2011
Management of soil erosion	1100 Mha	Medium evidence; high agreement	Lal (2004)
Prevent / reverse soil salinization	1000 Mha	Robust evidence, high agreement	Qadir et al. 2013; FAO 2016
Prevention of compaction	1000 Mha	Robust evidence, high agreement	Hamza and Anderson 2005; FAO and ITPS 2015
Fire management	Up to 350-490 Mha/yr	Robust evidence; medium agreement	Arora and Melton 2018; Randerson et al. 2012; Tansey et al. 2004
Management of landslides and natural hazards	100-500 Mha	Robust evidence; high agreement	FAO and ITPS 2015; Gariano and Guzzetti 2016
Ecosystem-based adaptation	>3000 Mha	Robust evidence; high agreement	Griscom et al. (2017)
Reduced deforestation and degradation	No global estimates	No evidence	
Management of pollution including acidification	~103 Mha	Limited evidence; low agreement	Oldeman et al. 1991
Management of invasive species / encroachment	No global estimates	No evidence	
Reforestation	See afforestation		
Restoration and avoided conversion of coastal wetlands	29 Mha	Limited evidence; high agreement	Griscom et al. (2017)
Biochar	Positive but not quantified		
Restoration and avoided conversion of peatlands	46 Mha	Limited evidence; high agreement	Griscom et al. (2017)
Afforestation	200-2580 Mha	Medium evidence; high agreement	Kreidenweis et al. 2016; Griscom et al., 2017; Popp et al., 2017
Avoidance of conversion of grassland to cropland	Up to 1.74 Mha/yr	Limited evidence; low agreement	Foley et al. (2011)
Enhanced weathering of minerals	Positive but not quantified	Limited evidence; low agreement	
Bioenergy and BECCS	Negative impact on up to 1500 Mha	Robust evidence; high agreement	Clarke et al., 2014; Popp et al., 2017; Smith et al., 2016

Increasing soil organic matter content is a measure to address land degradation. With around 12 Mha 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 land degradation, estimated to affect over 1.1 billion ha globally (Lal, 2004; Table 6.13).

Prevention of land degradation is strongly connected to implementation of improved cropland, livestock and grazing land management practices, such as those mentioned in recently published Voluntary Guidelines for Sustainable Soil Management (FAO 2017). Each one could potentially affect extensive surfaces, not less than 1000 million hectares. The Guidelines include a list of practices aiming 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, and soil sealing, soil compaction, and improving soil water management. Land cover and land cover change is a key factor and indicator of land degradation. In many drylands land cover is threatened by overgrazing, so that stocking rate and grazing management should be regulated to minimise and prevent advance of land degradation (Smith et al. 2016).

Burney et al.(2010) estimated that an additional global cropland area of 1111–1514 Mha 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-ITPS, 2014), increased food productivity has prevented upto 1111–1514 Mha from exploitation and land degradation (Table 6.13).

Agroforestry can help stabilise soils to prevent land degradation (Section 6.3.1.6), so given that there are is around 1000 Mha of land with >10% tree cover, agroforestry could benefit up to 1 billion ha of land.

Sustainable forest management and particularly forest restoration are key options to achieve the overarching strategies 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 2 billion hectares are suitable for forest and landscape restoration, of which 1.5 billion may be devoted to mosaic restoration (UNCCD 2012). Moreover, the Bonn Challenge's efforts are oriented to restore 150 million ha of deforested and degraded land by 2020, and 350 million ha by 2030 (http://www.bonnchallenge.org/content/challenge). Wolff et al. (2018) simulated that under a restoration and protection scenario (implementing restoration targets) there will be a global increase in net tree cover of about 400 million ha by 2050. At local level, the Brazil's Atlantic Restoration Pact aims to restore 15 million ha of forest areas in 40 years (Melo et al. 2013). The Y Ikatu Xingu campaign (launched in 2004) aims to contain deforestation and degradation processes by reversing the liability of 0.3 million ha in the Xingu Basin, Brazil (Durigan et al. 2013).

Agricultural diversification usually aims at increasing climate and food security resilience, such as the case of "climate smart agriculture" approaches (Lipper et al. 2014). Both objectives are closely related to land degradation prevention, potentially affecting 100–500 million hectares.

Control of soil erosion could have large benefits for addressing land degradation. Soil erosion control could benefit up to 150 Mha of land to 2050 (IPBES, 2018). Lal (2004) suggested interventions to prevent wind and water erosion (two of the four main interventions proposed to address land degradation), could restore 1.1 billion ha of degraded and desertified soils globally (Table 6.13).

Soil salinisation is among the four most widespread threats to world soil resources, both in drylands and irrigated areas (Montanarella et al. 2016). Its prevention/reversion can potentially improve extensive surfaces, not less than 1000 hectares. Excessive soil compaction is another important threat, but with favourable expectation if sustainable soil management is implemented, such as controlled agricultural transit, and stocking rate regulation in grazing lands. It could also potentilly affect extensive surfaces (Hamza et al.,2005).

For fire management, details of estimates of the impact of wildfires (and thereby the potential impact of their suppression) are given above is Section 6.4.3.1 (Table 6.13).

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 et al. 2015);(Gariano et al. 2016), but global potential is not quantified.

The areas available for ecosystem-based adaptation reported by Griscom et al. (2017), including areas for forest, peatland, wetland restoration reported elsewhere in this section exceed 3000 Mha globally.

There is no global estimate about the potential of reduced deforestation and forest degradation for addressing issues related to land degradation, in terms of area impacted. At regional scale, Santika et al. (2017) demonstrated that reduced deforestation (at a rate of 0.4 and 0.6 ha km^{-2} in the period 2012–2016) through the Village Forest strategy (Hutan Desa) in Indonesia (Sumatra and Kalimantan islands) contributed to reduce land degradation.

The global extent of chemical soil degradation (salinisation, pollution, and acidification) is about 103 Mha (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 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 29 Mha globally considered feasible for restoration (Griscom et al. 2017 ; Table 6.13).

Biochar could provide moderate benefits for the prevention or reversal of land degradation, by improving water holding capacity, improving nutrient use efficiency, managing heavy metal pollution and other co-benefits (Section 4.11.7; (Sohi,202), though the global effects are not quantified.

Considering that large areas (46 Mha) 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 6.13).

Afforestation and reforestation are land management options frequently used to address land degradation (see Section 6.4.3.1 for details; Table 6.13).

Shifting from grassland to tilled crops increases erosion and soil loss, so there are significant benefits for prevention or reversal of land degradation, by stabilising degraded soils (Chapter 3). Since cropland expansion during 1985 to 2005 was 1.74 Mha yr^{-1} (Foley et al.,2009), 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 therefore 1.74 Mha yr^{-1}, a small global benefit for control of land degradation (Tale 6.13).

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

Large-scale production of bioenergy can require significant amounts of land (Smith et al.,2016) Clarke and Jiang 2014; Popp et al. 2017), with as much as 1500 Mha in 2°C scenarios (Popp et al. 2017), increasing pressures for land conversion and land degradation (Table 6.13). However, bioenergy production can either increase (Robertson et al. 2017; Mello et al. 2014) or decrease (FAO 2011; 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 6.13.

6.4.4.2 Integrative response options based on value chain management

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

Table 6.14 Effects on land degradation of response options based on value chain management

Integrative response option	Potential	Confidence	Citation
Dietary change	400-2800 Mha	Robust evidence; high agreement	Bajželj et al. 2014; Stehfest et al. 2009; Tilman and Clark 2014
Reduced post-harvest losses	198 Mha/yr	Robust evidence; medium agreement	Kummu et al. 2012
Reduced food waste (consumer or retailer)	700 Mha	Robust evidence; medium agreement	Bajželj et al. 2014
Promotion of value-added products	No global estimates	No evidence	
Stability of food supply	No global estimates	No evidence	
Improved food transport and distribution	No global estimates	No evidence	
Urban food systems	No global estimates	No evidence	
Improved efficiency and sustainability of food processing, retail and agri-food industries	No global estimates	No evidence	
Increased energy efficiency in agriculture	No global estimates	No evidence	
Material substitution	No global estimates	No evidence	

Dietary change and waste reduction both result in decreased cropland and pasture extent (Bajželj et al. 2014a; Stehfest et al. 2009; Tilman and Clark 2014a), reducing the pressure for land degradation (Table 6.14).

Reduced post-harvest losses could spare 198 Mha 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.

There are no global estimates of the impact on land degradation of promotion of value-added products, improved food transport and distribution, urban food systems, improved efficiency and sustainability of food processing, retail and agri-food industries or increased energy efficiency in agriculture.

There is anecdotal evidence that the food price instability of 2007/2008 increased financial investment in crop expansion (especially through so-called land grabbing), but no quantification of the total amount of land acquired nor the possible impact of this crop expansion on degradation (McMichael and Schneider 2011; McMichael 2012). No studies were found linking material substitution to land degradation.

6.4.4.3 Integrative response options based on risk management

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

Table 6.15 Effects on land degradation of response options based on risk management

Integrative response option	Potential	Confidence	Citation
Establishing secure land tenure	<10 Mha	Medium evidence; low confidence	Garnett et al. 2018
Prevention of land grabbing	<45 Mha	Medium evidence; low confidence	Borras Jr et al. (2011); Balehegn (2015)
Management of urban sprawl	>20 Mha	Medium evidence; medium confidence	Zhang (2000)' Chen (2007)
Livelihood diversification	>10 Mha	Low evidence; low agreement	Liu & Lan 2015
Promotion of seed sovereignty	No global estimates	No evidence	
Early warning systems for disaster risk reduction	No global estimates	Low evidence; medium agreement	Pozzi et al. 2013
Commercial crop insurance	>0.5 Mha	Low evidence; medium agreement	Goodwin and Smith (2003); Wright and Wimberly (2013)

38 Mha of land worldwide are managed by indigenous peoples (Garnett et al.,2018). Evidence suggests that secure land tenure has been established for around 25% of Indigenous and community owned lands, leaving around 28 million hectares likely insecure. What percentage of this 28 million is at risk of degradation is not known, but it is likely less than 10 million given evidence that Indigenous peoples tend to be more successful managers of land to ward against degradation than other communities (RRI 2017).

At least 45 Mha, and as many as 82 MHa, of large-scale land acquisitions have occurred between 2005–2015 (Borras et al. 2011; Rulli et al. 2013; Balehegn 2015b), but it is unknown how much of this land is at risk of degradation.

Urban expansion has been pointed to as a major culprit in soil degradation in China, for example, affecting 20 million ha, almost one-sixth of the cultivated land total, and causing an annual grain yield loss of 10 million tons. 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. It is estimated that new city dwellers in developing countries will require 160–500 m^2 converted from non-urban to urban land (Barbero-Sierra et al. 2013).

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 9.3 Mha of lands (Liu et al.,2015). However,Warren(2002) provides conflicting evidence that more diverse-income households had increased degradation on their lands in Niger, and (Palacios et al.(2013) associate landscape fragmentation with increased livelihood diversification in Mexico.

Seed sovereignty may play a role in prevention and reversal of land degradation namely due to the likelihood of local seeds as being less dependent on inputs like 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 globally quantified figures.

EWS can have some positive impacts on prevention and reversal of land degradation, like the Global Drought Early Warning System (see above) (Pozzi et al. 2013b).

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 programs (including crop insurance and others) increased soil erosion by 0.135 tons per acre (Goodwin and Smith 2003). Wright and Wimberly (2013) found a 531,000 ha decline in grasslands in the Upper Midwest of the US 2006-2010 due to crop conversion driven by higher prices and access to insurance.

6.4.5 Potential of the integrated response options for addressing food security

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

6.4.5.1 Integrative response options based on land management

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

Table 6.16 Effects on food security of response options based on land management

Integrative response option	Potential	Confidence	Citation
Increased soil organic matter content (and reduced losses)	60-225 million people	Low evidence; medium agreement	Frank et al. (2017)
Improved cropland management	>1000 million people	Robust evidence, high agreement	Campbell et al. 2014; Lipper et al. 2014
Improved livestock management	>1000 million people	Robust evidence, high agreement	Herrero et al. 2016
Improved grazing land management	>1000 million people	Robust evidence, high agreement	Herrero et al. 2016
Increased food productivity	3000 million people	Robust evidence; high agreement	Erisman et al. (2008)
Agro-forestry	Upto 1300 million people	Limited evidence; high agreement	Sasha, A. et al. 2018
Sustainable forest management and forest restoration	No global estimates	No evidence	
Agricultural diversification	>1000 million people	Robust evidence, high agreement	Birthal et al. 2015; Massawe et al. 2016; Waha et al. 2018
Management of soil erosion	760 million people/yr	Limited evidence; low agreement	Lal (1998)
Prevent / reverse soil salinization	1-100 million people	Limited evidence, medium agreement	Qadir et al. 2014
Prevention of compaction	1-100 million people	Medium evidence; high agreement	Anderson and Peters 2016
Fire management	~78 million people	Limited evidence; low agreement	FAO 2015
Management of landslides and natural hazards	1-100 million people	Limited evidence; moderate agreement	Campbell 2015
Ecosystem-based adaptation	>200 million people	Medium evidence; high agreement	Munang et al. (2015)
Reduced deforestation and degradation	No global estimates	No evidence	
Management of pollution including acidification	Increase annual crop yields 30-135 Mt globally; feeds 120-540 million people	Limited evidence; low agreement	Shindell et al., 2012
Management of invasive species / encroachment	No global estimates	No evidence	
Reforestation	See afforestation		
Restoration and avoided conversion of coastal wetlands	Very small negative but not quantified	Limited evidence; low agreement	
Biochar	Potentially negative impact on 640-4160 million people	Limited evidence; low agreement	Calculated from values in Smith (2016)
Restoration and avoided conversion of peatlands	Negative impact on 21-31 million people	Limited evidence; low agreement	Clark & Tilman 2017; FAO, 2018
Afforestation	Negative impact on > 100 million people	Medium evidence; high agreement	Kreidenweis et al., 2016; Boysen et al., 2017; Frank et al., 2017
Avoidance of conversion of grassland to cropland	Negative impact on 16.4 million people	Limited evidence; low agreement	Clark & Tilman 2017; FAO, 2018
Enhanced weathering of minerals	No global estimates	No evidence	
Bioenergy and BECCS	Negative impact on 110 million people	Robust evidence, high agreement	Fujimori et al. (in review)

Increasing soil organic matter stocks can increase yield and improve yield stability (Lal 2006; Pan et al.,2009;(Soussana et al.,2018). 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 maize for wheat, rice and maize, respectively, for every 1t C ha^{-1} increase in soil organic carbon in the root zone. Increasing soil organic carbon by 1 t C 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 6.16).

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 nutrient overuse in should be avoided in order not to cause environmental impacts of agriculture (Mueller et al. 2012). This improvement can impact not less than 1000 million people.

In the same way, 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 million people (Herrero et al.,2016). Ruminants are efficient converters of grass into humanly edible energy and protein and grassland-based food production can produce food with a comparable carbon footprint as 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. 2010).

Improved grazing land management includes grasslands, rangelands and shrublands, all sites pastoralism is practiced. In general terms, continuous grazing may cause severe damages upon topsoil quality, such as compaction and kneading. This damage may be reversed by short grazing exclusion periods under rotational grazing systems (Greenwood et al.,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.

Increased food productivity has fed many millions of people, who could not have otherwise been fed. (Erisman et al.,2008) estimated that over 3 billion people worldwide could not have been fed without increased food productivity arising from nitrogen fertilisation (Table 6.16).

Currently, over 1.3 billion people are trapped 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.

There is no availability of global estimates about the effects of forest management and restoration activities on the number of nourished people. Nevertheless, forests play a major role to provide 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. Managed natural forests, shifting cultivation, agroforestry systems are demonstrated to be crucial to food security and nutrition of hundreds of million people in rural landscapes worldwide (see Vira et al., 2015).

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. 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. 2018b).

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 assume per-capita annual grain consumption in developing countries to be 250 kg yr^{-1}, the loss of 190 Mt yr^{-1} of cereals is equivalent to that consumed by 760 million people annually (Table 6.16).

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. 2014). Soil compaction affects crop yields, so prevention of compaction could benefit an estimated 1–100 million people globally (Anderson et al.,2016).

FAO (2015) calculated the damage between 2003 and 2013 and found that forest fires damaged a total of 4.9 Mha of crops, valued at roughly USD 689 million, with the vast majority in Latin America. If average crop yields in Latin America are assumed to be about 4 tonne ha^{-1} yr^{-1} (average of wheat and maize yields in Brazil and Argentina), 4.9 Mha of crops is equivalent to 19.6 Mt yr^{-1} of cereals lost. Assuming annual grain consumption per capita in developing countries to be 250 kg yr^{-1}, the loss of 19.6 Mt yr^{-1} would remove cereal crops equivalent to that consumed by 78 million people (Table 6.16).

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

Over 200 million people in Africa alone currently suffer from debilitating symptoms of chronic to severe malnutrition, and could benefit from ecosystem-based adaptation (Munang et al., 2015).

There is no availability of global estimates on the impact of reduced deforestation and forest degradation on the number of nourished people. According to Erb et al. (2016), deforestation would not be needed to feed the global population by 2050, in terms of quantity and quality. At local level, Cerri et al. (2018) suggested that reduced deforestation, along with integrated cropland-livestock management, would positively impact more than 120 million people in the Cerrado, Brazil.

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 million metric tonnes due to ozone reductions in 2030 and beyond. If annual grain consumption per capita in developing countries is assumed as 250 kg yr^{-1}, 30–135 million tonnes would be equivalent to 120–540 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, though 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 6.16).

Biochar on balance, could provide moderate benefits for food security by improving yields by 25% in the tropics, but with no effect in temperate regions (Jeffery et al.,2017), or through improved water holding capacity and nutrient use efficiency (Chapter 5; Sohi,2012), 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 40–260 Mha of land would be required for biomass feedstock to deliver 2.57 $GtCO_2$-eq yr^{-1} of CO_2 removal. To estimate the maximum potential impact of food security, if the land for biochar feedstock production were to displace cropland, this would be equivalent to 160–1040 Mt grain yr^{-1} (assuming an average cereal yield of 4 t $ha^{-1}yr^{-1}$), which is equivalent to cereal crops consumed by 640–4160 million people (assuming the annual grain consumption per capita in developing countries to be 250 kg yr^{-1}) (Table 6.16).

Around 14-20% (56–80 Mha) of the worlds 400 Ma of peatlands are used for agriculture, mostly for meadows and pasture, meaning that if all of these peatlands were removed from production, 56–80 Mha or 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 per hectare per year (calculated from land footprint of beef/mutton in (Clark and Tilman 2017)) and average protein consumption in developing countries of 25.5 kg protein per year (equivalent to 70g/person/day; FAO, 2018), this would be equivalent to 21–31 million people no longer fed from this land (Table 6.16).

Afforestation and reforestation negatively impact food security (Boysen et al., 2017; Frank et al., 2017; Kreidenweis et al. 2016). It is estimated that large-scale afforestation plans causes increases in food prices of 80% by 2050 (Kreidenweis et al. 2016), and more general mitigation measures in the 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-affects 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.

Cropland expansion during 1985 to 2005 was 1.74 Mha yr^{-1} (Foley et al., 2009). Given that cropland productivity (global average of 250 kg protein ha yr^{-1} for wheat; (Clark and Tilman 2017) is greater than that of grassland (global average of about 10 kg protein ha 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 per year globally. Given an average protein consumption in developing countries of 25.5 kg protein per year (equivalent to 70g/person/day; FAO, 2018), this is equivalent to the protein consumption of 16.4 million people each year (Table 6.16).

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. 2014b) Popp et al. 2017; Wise et al. 2009) Only one study was found linking bioenergy to the population at risk of hunger; they estimate an additional 110 million people will be at risk of hunger in a 1.5C scenario (Table 6.16). However, this estimate includes both the effect of competition for land due to bioenergy use and pricing of non-CO_2 emissions.

6.4.5.2 *Integrative response options based on value chain management*

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

Table 6.17 Effects on food security of response options based on value chain management

Integrative response option	Potential	Confidence	Citation
Dietary change	821 million people	Robust evidence, high agreement	Tilman & Clark, 2014; Aleksandrowic et al., 2016
Reduced post-harvest losses	1000 million people	Robust evidence; high agreement	Kummu et al. (2012)
Reduced food waste (consumer or retailer)	700-1000 million people	Limited evidence; medium agreement	Kummu et al. (2012); FAO (2018)
Promotion of value-added products	821 million	Robust evidence; high agreement	FAO (2018)
Stability of food supply	> 1 million but probably <100 million: estimate ~ 20 million	Limited evidence; medium agreement	Fujimori et al. (2018); Parry et al. (2005); Nandy et al. (2016)
Improved food transport and distribution	700-1000 million people	Limited evidence; medium agreement	Kummu et al. (2012); FAO (2018)
Urban food systems	Up to 1260 million people	Limited evidence; medium agreement	de Zeeuw & Drechsel 2015; Padgham et al. 2015; Specht et al., 2014; Benis & Ferrão, 2017
Improved efficiency and sustainability of food processing, retail and agri-food industries	500 million people	Limited evidence; medium agreement	World Bank (2017)
Increased energy efficiency in agriculture	Up to 2500 million people	Limited evidence; medium agreement	IEA (2014)
Material substitution	No global estimates	No evidence	

Dietary change can free up agricultural lands for additional production (Bajželj et al. 2014a; Stehfest et al. 2009; Tilman and Clark 2014a) and reduce the risk of some diseases (Tilman and Clark 2014a; Aleksandrowicz et al. 2016b), with large positive impacts on food security (Table 6.17).

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, and measures such as improved food transport and distribution could also contribute to this waste reduction (Table 6.17).

Since 810 million people are undernourished (FAO, 2018), this sets the maximum number of those that could potentially benefit from promotion of value-added products.

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. 2012;Brinkman et al.,2010 ; (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 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 expenditures 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. 2018).

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 6.17).

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 estimated number of people worldwide lacking access to clean energy and instead rely on biomass fuels for their household energy needs (IEA, 2014).

No studies were found linking material substitution to food security.

6.4.5.3 Integrative response options based on risk management

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

Table 6.18 Effects on food security of response options based on risk management

Integrative response option	Potential	Confidence	Citation
Establishing secure land tenure	>1 million likely	Medium evidence; low confidence	Deiniger & Feder (2009); Bruce (1998)
Prevention of land grabbing	12 million	Medium evidence; medium agreement	Adnan (2013); Davis et al. (2014)
Management of urban sprawl	>1 million likely	Limited evidence; low agreement	Chen (2007
Livelihood diversification	>100 million	Limited evidence; low agreement	Morton 2007
Promotion of seed sovereignty	>100 million	Medium evidence; medium agreement	Altieri 2012
Early warning systems for disaster risk reduction	> 1 million	Limited evidence; medium agreement	Genesio et al. 2011; Hillbruner and Moloney 2012
Commercial crop insurance	>1 million likely	Limited evidence; medium agreement	Claassen et al. 2011; Goodwin et al. 2004

Reviews of links between land tenure and food security show some qualitative positive synergies, but little quantification of numbers of people or lands affected (Maxwell & Wiebe 1999). The evidence is very mixed on whether securing tenure leads to agricultural investment (Deininger et al.,2009)), with evidence in Africa particularly inconclusive (Fenske 2011). However, one study in Burkina Faso found that perceived tenure insecurity among households led to an 8.9% reduction in agricultural productivity (Linkow 2016). Given that at least 1 million households in sub-Saharan Africa alone do not have secure land tenure to food production lands (Bruce 1998), we have taken that as a range for those who could be potentially assisted by land tenure policies.

Reports suggest that recent land grabbing has affected 12 million people globally in terms of declines in welfare (and presumably food security as well) (Adnan 2013; Davis et al. 2014).

Evidence in the US indicates ambiguous trends between sprawl and food security; on one hand most urban expansion in the US 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 were experiencing 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 US, 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 million tons of grain production from 1998–2003 in eastern China was attributed to urbanisation (Catena and 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 (Barret et al. 2001;Niehof 2004), but there is little global quantification.

Seed sovereignty provides considerable benefits for food security because of the increased ability of farmers to revive and strengthen local food systems (McMichael and Schneider 2011); several 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 provision many hundreds of millions of consumers (Altieri et al. 2012;McGuire and Sperling 2016), therefore keeping their ability to do so open through seed sovereignty is important.

When EWS 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 EWS (Shisanya and Mafongoya 2016). Additionally, famine early warning systems have been successful in Sahelian Africa to alert authorities to 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).

Food security benefits positively from crop insurance, as crop insurance has generally lead to (modest) expansions in cultivated land area and increased food production (Claassen et al. 2011; Goodwin et al. 2004)

6.5 Managing interactions and interlinkages

For the integrative response options decribed in Section 6.3, their potential to contribute to each of the land challenges: climate change mitigation, climate change adaptation, desertification, land degradation and food security were quantified (were possible) in Section 6.4. In this section, we collate all of the impacts of each integrative response option across all of the land challenges, and express these in terms of co-benefits and trade-offs, quantified as large, moderate, small or negligible, as described in Table 6.3. In Section 6.5.1 we present this summary for land management response options, in Section 6.5.2 for options based on value chain management and in Section 6.5.3 for options based on risk management. These Sections (6.5.1, 6.5.2 and 6.5.3) also consider, for each integrative response option, issues of sink saturation and reversibility, and relative cost of each option. In Section 6.5.4., the impacts of integrated response options on Nature's Contributions to People and the UN sustainable development goals are described, and in Section 6.5.5 the applicability and barriers to implementation of the main integrative response options are assessed spatially (Section 6.5.5.1), to identify the regions in which the challenges are most prevalent, where the integrative response options are likely to be most effective, and where barriers to implementation are most likely to occur. Section 6.5.5 is completed by a description of how interlinkages between challenges and response options are represented in future scenarios (Section 6.5.5.2), before describing the link between response options and policies (6.5.5.3) which are explored in Chapter 7.

In Sections 6.5.2, 6.5.3 and Section 6.5.4, a number of issues related to the response options, co-benefits and adverse side-effects should be noted:

1) The response options often overlap (see Section 6.3), so are not additive. For example, increasing food productivity will involve changes to cropland, grazing land and livestock management, which in turn my include increasing soil carbon stocks. The response options should not therefore be summed, nor regarded as entirely mutually exclusive interventions. Cross reference to the relevant sections are made where overlaps occur.
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, e.g. 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 integrative response options have been quantified as far as possible in Section 6.4, there is no equivalence implied in terms co-benefits or adverse side-effects, either in number or in magnitude of the impact, i.e. one co-benefit *does not equal* one adverse side-effect. As a consequence:
    a. Large co-benefits for one challenge might outweigh relatively minor adverse side-effects in addressing another challenge.
    b. Some response options may deliver mostly co-benefits with few adverse-side effects, but the co-benefits might be small in magnitude, i.e. the response options do no harm, but present only minor co-benefits.
4) A number of co-benefits and adverse side-effects are context specific; the context specificity is discussed in each of the sub-sections of Sections 6.5.2, 6.5.3 and 6.5.4 where relevant, and are examined further in Section 6.5.5.1.

In this section we deal only with integrated response options, not the policies that are currently / could be implemented to enable their application; that is the subject of Chapter 7.

Each of the response options is dealt with in sections 6.5.2, 6.5.3 and 6.5.4 below. The main co-benefits and adverse side-effects described in these sections are summarised in Figure 6.6.

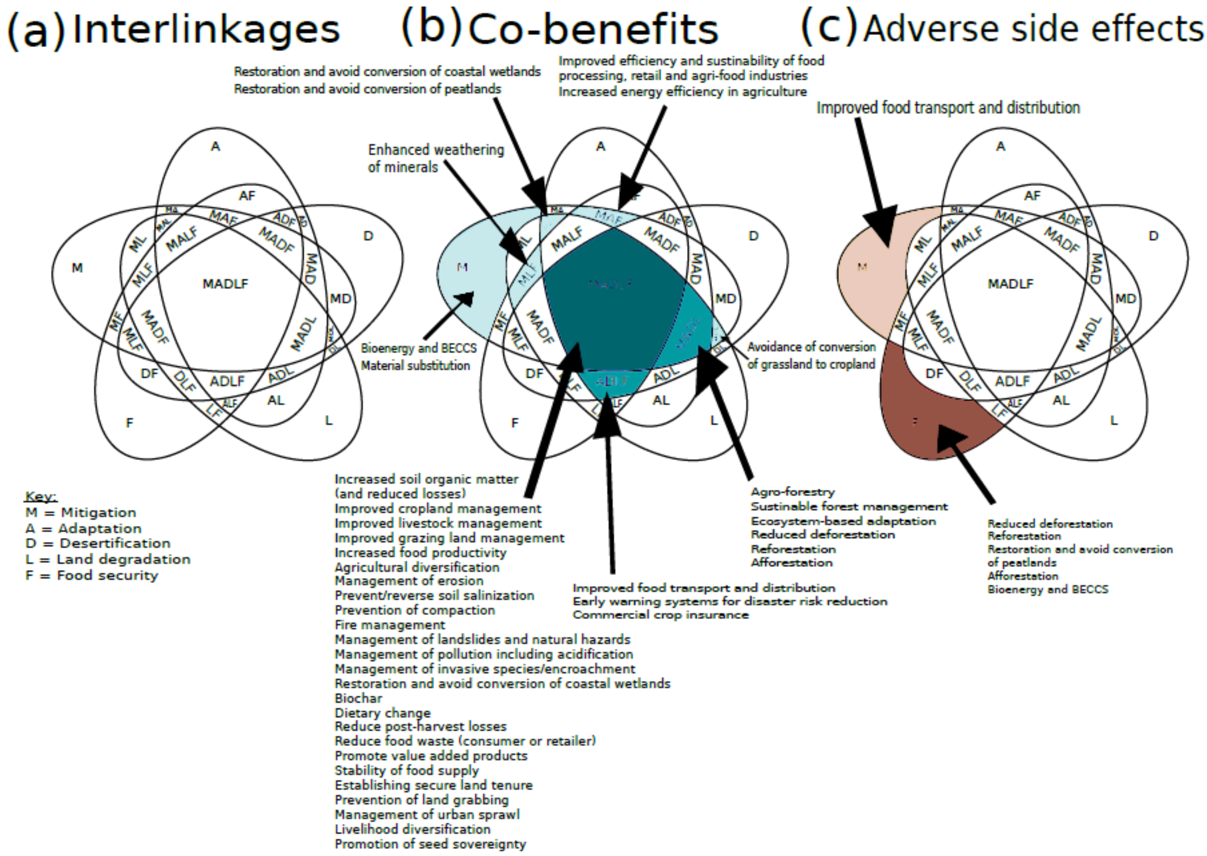
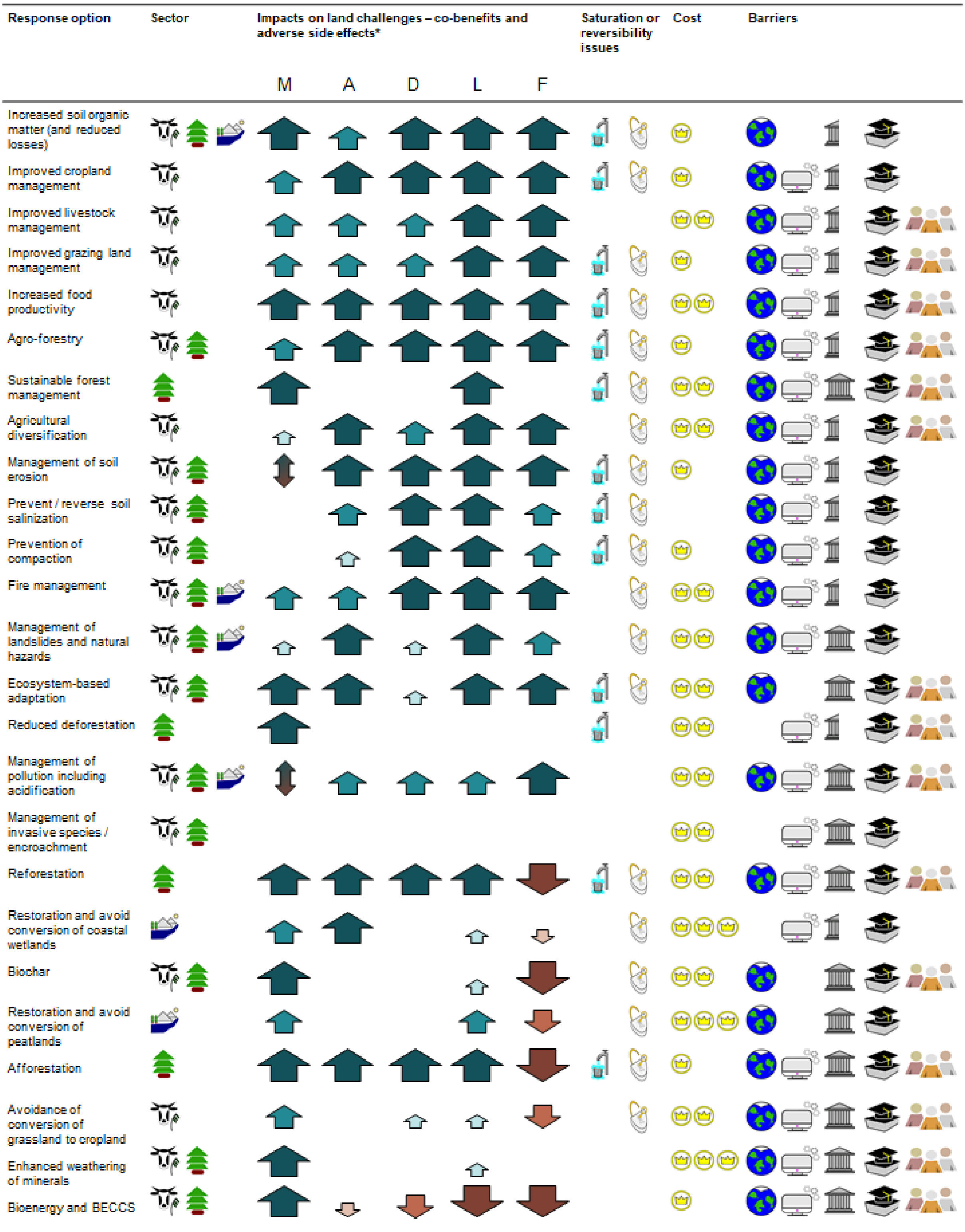


Figure 6.6 Summary of a) interlinkages between the main land challenges mitigation (M), adaptation (A), desertification (D), land management (L) and food security (F), b) the co-benefits delivered by integrative response options across the five land challenges, and c) the adverse side-effects incurred by integrative response options across the five land challenges. The depth of colour represents the magnitude of the co-benefit (dark blue/red = large; mid-blue/red = medium; light blue/red = small; see Table 6.4 for definitions / thresholds between categories)

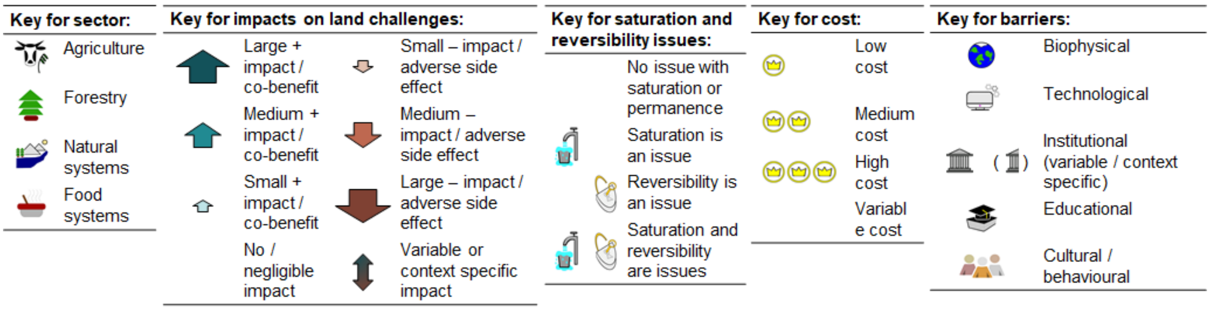
6.5.1 Integrative response options based on land management

In addition to summarising the scale of co-benefits and adverse side-effects associated with each response option, as quantified in Section 6.4, this section also discusses permanence/saturation issues, costs and barriers of land management response options are summarised below in Table 6.19. The subsections below deal with each response option.

Table 6.19 Summary of co-benefits, adverse side effects, permanence/saturation issues, costs and barriers of land management response options to address land challenges



* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security



6.5.1.1 Increased soil organic matter content (and reduced losses)

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Increased soil organic matter (and reduced losses)									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Increased soil organic matter content provides ***large co-benefits*** for climate mitigation by creating soil carbon sinks (Section 6.4.1.1), ***moderate co-benefits*** for climate adaptation by improving the resilience of food crop production systems to future climate change (Chapter 2; Section 6.4.2.1; Porter et al. 2014), ***large co-benefits*** for prevention or reversal of desertification by improving soil health and sustainable use of land in arid areas (Chapter 3; Section 6.4.3.1; D'Odorico et al. 2013), ***large co-benefits*** for prevention or reversal of land degradation by forming a major component of sustainable land management (Chapter 4; Section 6.4.4.1; Altieri and Nicholls 2017) and ***large co-benefits*** for food security by increasing yield and yield stability to enhance food production (Chapter 5; Section 6.4.5.1; Pan et al. 2009). There are ***few adverse side-effects*** across the challenges (Bustamante et al. 2014b; Smith 2016a) as long as soil organic matter sinks are not increased by methods that increase the emissions of other greenhouse gases (Liao et al. 2016). The soil carbon sink, however, both saturates and is reversible (Smith 2013). Increasing soil organic matter content is a low cost option, which can be cost negative (Smith et al.,2008 ; McKinsey and Company 2009). Barriers to implementation include biophysical (e.g., soil type; Baveye et al. 2018), technological (e.g., difficult to measure and verify; Smith 2006), can be institutional in some regions (e.g., lack of institutional capacity; (Bustamante et al. 2014), educational (e.g., poor knowledge of best practices among farmers; (Reichardt et al. 2009), though cultural / behavioural barriers are likely to be small compared to other barriers (Smith et al. 2007; Wollenberg et al. 2016).

6.5.1.2 Improved cropland management

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Improved cropland management									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Improved cropland management provides ***moderate co-benefits*** for climate mitigation by reducing greenhouse gas emissions and creating soil carbon sinks in the range of 1.4 $GtCO_2\ yr^{-1}$ (Chapter 2; Section 6.4.1.1;Smith et al.,2008 , 2014), ***large co-benefits*** for climate adaptation by improving the resilience of food crop production systems to future climate change (Chapter 2; Section 6.4.2.1; Porter et al. 2014), ***large co-benefits*** for prevention or reversal of desertification by improving sustainable use of land in arid areas (Chapter 3; Section 6.4.3.1; Bryan et al. 2009; Chen et al. 2010), ***large co-benefits*** for prevention or reversal of land degradation by forming a major component of sustainable land management (Chapter 4; section 6.4.4.1; (Labrière et al. 2015b) and ***large co-benefits*** for food security by improving agricultural productivity for food production (Chapter 5; Section 6.4.5.1; Porter et al. 2014). There are few adverse side-effects across the challenges (Bustamante et al. 2014). While the soil carbon sink component of improved cropland management both saturates and is reversible (see section on increasing soil organic matter content (Smith 2013), other components (such as reduced methane and nitrous oxide emissions) do not. However, if practices under improved cropland management are discontinued, the beneficial impacts will also cease. Improved cropland management is a low cost option, which can be cost negative (Smith et al.2008, 2014b). Barriers to implementation include biophysical (e.g., land access; Bryan et al. 2009; (Bustamante et al. 2014) technological (e.g., need for further development of nitrification inhibitors; (Singh and Verma 2007), can be institutional in some regions (e.g., poor sustainability frameworks; (Madlener et al. 2006), educational (e.g., lack of knowledge; (Reichardt et al. 2009), and cultural / behavioural (e.g., promotion of cover crops needs to account for farmers' needs; Roesch-McNally et al. 2017).

6.5.1.3 Improved livestock management

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Improved livestock management									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Improved livestock management provides ***moderate co-benefits*** for climate mitigation by reducing greenhouse gas emissions, particularly from enteric methane and manure management in the range of 0.5–0.7 $GtCO_2$ yr^{-1} (Chapter 2; Section 6.4.1.1; Smith et al.2008 , 2014), ***moderate co-benefits*** for climate adaptation by improving the resilience of livestock production systems to future climate change (Chapter 2; Section 6.4.2.1; Porter et al. 2014), ***moderate co-benefits*** for prevention or reversal of desertification by tackling overgrazing in arid areas (Chapter 3; Section 6.4.3.1; (Archer et al.,2011), ***large co-benefits*** for prevention or reversal of land degradation by allowing for reduced stocking density (Chapter 4; Section 6.4.4.1; Tighe et al. 2012) and ***large co-benefits*** for food security by improving livestock sector productivity for food (Chapter 5; Section 6.4.5.1; Herrero et al. 2016). There are ***few adverse side-effects*** across the challenges (Bustamante et al. 2014b). There are no saturation or reversibility issues associated with improved livestock management. The different practices contributing to improved livestock managed vary greatly in cost, with some cost negative (such as improved productivity; Smith et al.2008 ; Herrero et al. 2016) and others expensive (such as some of the dietary additives; McKinsey and Co., 2009). Barriers to implementation include biophysical (e.g., climate suitability of different cattle breeds in a changing climate; Thornton et al. 2009; Rojas-Downing et al. 2017), technological (e.g., many dietary additives are still at low technology readiness level; Beauchemin et al., 2008), can be institutional in some regions (e.g., need for extension services; Ndoro et al., 2014), educational (e.g., poor knowledge of best animal husbandry practices among farmers; Ndoro et al., 2014), and cultural / behavioural (e.g., strong cultural importance of livestock in some communities (Herrero et al. 2016).

6.5.1.4 Improved grazing land management

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Improved grazing land management									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Improved grazing land management provides ***moderate co-benefits*** for climate mitigation by increasing soil carbon sinks and reducing greenhouse gas emissions in the range of 1.3 $GtCO_2$ yr^{-1} (Chapter 2; Section 6.4.1.1; Herrero et al. 2016), ***moderate co-benefits*** for climate adaptation by improving the resilience of grazing lands to future climate change (Chapter 2; Section 6.4.2.1; Porter et al. 2014), ***moderate co-benefits*** for prevention or reversal of desertification by tackling overgrazing in arid areas (Chapter 3; Section 6.4.3.1; (Archer et al.,2011), ***large co-benefits*** for prevention or reversal of land degradation by optimising stocking density (Chapter 4; Section 6.4.4.1; Tighe et al. 2012), and ***large co-benefits*** for food security by improving livestock sector productivity for food (Chapter 5; Section 6.4.5.1; Herrero et al. 2016). There are ***few adverse side-effects*** across the challenges (Bustamante et al. 2014). While the soil carbon sink component of improved grazing land management both saturates and is reversible (see section on increasing soil organic matter content; (Smith 2013), other components (such as reduced methane and nitrous oxide emissions) do not. However, if practices under improved grazing land management are discontinued, the beneficial impacts will also cease. Improved grazing land management is a low cost option, which can be cost negative (Smith et al. 2008; McKinsey and Co., 2011). Barriers to implementation include biophysical (e.g., unless degraded, grazing lands are already closer to saturation than croplands; Smith et al. 2015), technological (e.g., need for further development of nitrification inhibitors; (Singh and Verma 2007), can be institutional in some regions (e.g., need for extension services; Ndoro et al., 2014), educational (e.g., poor knowledge of best animal husbandry practices among farmers; Ndoro et al., 2014), and cultural / behavioural (e.g. strong cultural importance of livestock and traditional practices in some communities (Herrero et al. 2016).

6.5.1.5 Increased food productivity

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Increased food productivity									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Increased food productivity, if delivered sustainably (e.g., through sustainable intensification) could provide large co-benefits for mitigation (Section 6.4.1.1.). By reducing pressure on land and food production, there are also large co-benefits for adaptation (Chapter 2; Section 6.4.2.1; Campbell et al. 2014). There can be large co-benefits for prevention of desertification (Chapter 3; Section 6.4.3.1;(Dai 2010) and large co-benefits for prevention or reversal of land degradation (Chapter 4; Section 6.4.4.1; Clay et al., 1995). There are large co-benefits for food security, through increased production of food (Chapter 5; Section 6.4.5.1; Godfray et al. 2010; Tilman et al. 2011; Godfray and Garnett 2014). Intensification has led to a wide range of negative impacts on water quality, air quality and biodiversity (Tilman et al. 2011a), but sustainable intensification (by definition) aims to increase food productivity without adverse side-effects (Garnett et al.,2013), since it would not be considered sustainable intensification if there were negative impacts. Barriers to implementation include technological barriers, for example limited ability to define and measure indicators of sustainable intensification (Barnes and Thomson 2014), biophysical, since increasing food productivity can be limited by climatic and environmental factors (Olesen et al. 2002) institutional (e.g., better access to credit, services, inputs and markets, Schut et al., 2016), educational (e.g., educational needs of women; Pretty and Bharucha 2014), and cultural / behavioural (Martin et al. 2015).

6.5.1.6 *Agro-forestry*

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Agro-forestry									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Agro-forestry provides ***moderate co-benefits*** for climate mitigation by increasing carbon sinks in vegetation and soils (Chapter 2; Section 6.4.1.1; Delgado et al., 2011; (Mbow et al. 2013) in the range of 1.4 $GtCO_2$ yr^{-1} (Griscom et al. 2017a), ***large co-benefits*** for climate adaptation by improving the resilience of agricultural lands to future climate change (Chapter 2; Section 6.4.2.1; Mbow et al. 2013), ***large co-benefits*** for prevention or reversal of desertification by providing perennial vegetation in arid areas (Chapter 3; Section 6.4.3.1; (Ramachandran Nair et al. 2010b; Lal 2001), and ***large co-benefits*** for prevention or reversal of land degradation by stabilising soils through perennial vegetation (Chapter 4; Section 6.4.4.1; Narain et al. 1997; Lal 2001). Depending on how implemented, adding trees to the landscape could reduce the land area available for food production, though well planned agro-forestry can enhance productivity (Bustamante et al. 2014b), so could have ***large co-benefits*** for food security (Chapter 5; Section 6.4.5.1; Sasha et al., 2018). There are ***few adverse side-effects*** across the challenges (Bustamante et al. 2014b), though removal of land for food production could occur. The carbon sink provided by agro-forestry both saturates and is reversible (see also section on increasing soil organic matter content; Smith 2013). Agro-forestry is a low cost option (Smith et al. 2014b). Barriers to implementation include biophysical (susceptibility to pests; Sileshi et al. 2008), institutional in some regions (e.g., seed availability; Lillesø et al. 2011), educational (e.g., poor knowledge of how best to integrate trees into agro-ecosystems; Meijer et al. 2015) and cultural / behavioural (e.g., farmers perceptions; Meijer et al., 2015). There are likely to be relatively few technological barriers (Smith et al. 2007).

6.5.1.7 *Sustainable forest management and forest restoration*

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Sustainable forest management									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Sustainable forest management and forest restoration provide ***large co-benefits*** for climate mitigation by conserving and enhancing carbon stocks in forests and long-lived products and by providing wood used to reduce GHG emissions through material and energy substitution (Section 6.4.1.1; Smith et al. 2014). Given the trade-offs between forest management options (i.e., increasing forest carbon stocks vs. increasing the substitution effects), it is the overall climate impact of both options that should be maximised in a given time frame. There are no data to quantify the impacts of sustainable forest management and forest restoration on adaptation (Sections 6.4.2.1 and 6.4.3.1), but there are ***large co-benefits*** for prevention or reversal of land degradation, e.g., by affecting land stabilisation, water and microclimatic regulation (Section 6.4.4.1, e.g. Locatelli et al. 2015b; Alkama and Cescatti 2016). For example, sustainable forest management such as selective logging allows to retain substantial levels of carbon stocks, biodiversity, and timber volumes (Putz et al. 2012), and can therefore offer co-benefits in terms and mitigation, adaptation and prevention of land degradation. There are no studies to assess the impact of sustainable forest management or forest restoration on food security (Section 6.4.5.1). There are few possible ***adverse side-effects*** across the challenges. The carbon sink provided by forest management saturates and is reversible (Smith et al. 2014b). To this regard, integrating adaptation and mitigation allows reducing the impacts of climate change on forests, as such impacts may jeopardise the permanence of carbon storage (Locatelli et al. 2011). Forest management affects the climate also through biophysical effects and the emissions of biogenic volatile organic compounds (BVOCs), which are both influenced by species composition. Forest management strategies aiming at maximise the carbon sink (e.g., fast-growing tree monoculture) may reduce biodiversity and options for ecological adaptation (Locatelli et al. 2015b). Barriers to implementation of sustainable forest management practices are mainly educational (limited knowledge of the most appropriate techniques) and institutional (e.g., better access to credit and markets, etc.). Forest certification may be an effective instrument to promote sustainable forest management (Bustamante et al. 2016).

6.5.1.8 Agricultural diversification

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Agricultural diversification									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Agricultural diversification is a collection of practices aimed at derviving more crops or products per unit of area (e.g., intercropping) or unit of time (e.g., double cropping, ratoon crops etc.). It has ***small co-benefits*** for mitigation (Section 6.4.1.1), but has the potential to deliver ***large co-benefits*** for adaptation to climate change (Section 6.4.2.1). Diversification could also deliver ***moderate co-benefits*** for the prevention of desertification (Section 6.4.3.1) and ***moderate co-benefits*** for prevention and reversal of land degradation (Section 6.4.4.1), since it can reduce the pressure on land (Lambin and Meyfroidt 2011). It provides ***large co-benefits*** for the achievement of food security (Chapter 5; Section 6.4.5.1; Birthal et al. 2015; Massawe et al. 2016; Waha et al. 2018) and household income (Pellegrini and Tasciotti 2014). There are likely ***few adverse side effects*** (Massawe et al. 2016; Waha et al. 2018a). However, diversification is not always economically viable (Barnes et al. 2015), and technological, biophysical, educational, and cultural barriers may emerge that limit the adoption of more diverse farming systems by farmers (Barnett and Palutikof 2015; Ahmed and Stepp 2016b; Roesch-McNally et al. 2016). 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 (Martin and Lorenzen 2016; Waha et al. 2018a).

6.5.1.9 Management of soil erosion

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Management of soil erosion									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

The management and control of soil erosion has ***uncertain impacts*** on mitigation since the final fate of eroded material is still debated, and at the global level is considered uncertain (Chapter 2; Section 6.4.1.1; Hoffmann et al., 2013). Soil erosion control measures can deliver ***large co-benefits*** for adaptation, since soil erosion control prevents land degradation and desertification, thereby improving the resilience of agriculture to climate change (Chapter 2; Section 6.4.2.1; Lal, 1998). It can deliver ***large co-benefits*** for prevention and reversal of desertification and ***large co-benefits*** for prevention and reversal of land degradation, since soil erosion is the most important soil degradation process (Chapters 3 and 4; Sections 6.4.3.1 and 6.4.4.1; FAO and ITPS 2015). Erosion control measures have the potential to deliver ***large co-benefits*** for food security, mainly through the preservation of crop productivity (Chapter 5; Section 6.5.4.1; Lal, 1998). There are likely ***no adverse side-effects*** from soil erosion control measures. The most prominent barriers to implementation include institutional factors (e.g., laws, regulations of use), technological (e.g., limited technology choices), educational (lack of farmer knowledge of erosion control measures), social, and economic factors (e.g., credit support, tax discounts). For instance, in Ethiopia farmers have shown an increased understanding of the soil erosion problem, but soil conservation programs face a host of barriers related to limited access to capital, limited benefits, land tenure insecurity, limited technology choices and technical support, and poor community participation (Haregeweyn et al. 2015).

6.5.1.10 Prevent / reverse soil salinisation

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Prevent / reverse soil salinization									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Techniques to prevent and reverse soil salinisation include groundwater management by drainage systems and/or crop rotation, and eventual use of amendments to alleviate soil sodicity. There are no studies to quantify the impacts on mitigation (Section 6.4.1.1), but there are ***moderate co-benefits*** for adaptation, since these practices allow existing crop systems to be maintained and crop shifting to be reduced (Section 6.4.2.1; UNCTAD 2011; Dagar et al. 2016). Practices to tackle soil erosion can deliver ***large co-benefits*** for prevention and reversal of desertification (Sections 3.6 and 6.4.3.1; Rengasamy 2006; Dagar et al. 2016) and ***large co-benefits*** for prevention and reversal of land degradation (Chapter 4; Section 6.4.4.1), since soil salinisation is a main driver of both desertification and land degradation in the world's drylands. Prevention of soil salinisation delivers ***moderate co-benefits*** for food security by maintaining existing crop systems, and helping to close yield gaps in rainfed crops (Sections 5.8 and 6.4.5.1). There are likely to be ***few adverse side-effects***, apart from potential additional fossil fuel use for irrigation or increasing the efficiency of water use usually means reduced yields at some level. Barriers depend on how salinisation and sodification are tackled, but can include biophysical (e.g., lack of alternative water sources; Bhattacharya et al. 2015; Dagar et al. 2016), technological (e.g., lack of appropriate irrigation technology; Machado and Serralheiro 2017; CGIAR 2016; Bhattacharyya et al. 2015), institutional (lack of alternative irrigation infrastructure; Evans and Sadler 2008; CGIAR 2016), educational (poor knowledge of the causes and salinisation and how to address it; Greene et al. 2016; Dagar et al. 2016), and cultural / behavioural (persistence of traditional practices; Greene et al. 2016; Dagar et al. 2016).

6.5.1.11 Prevention of compaction

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Prevention of compaction									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

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). The global mitigation potential has not been quantified (Section 6.4.1.1; Chamen et al. 2015; Epron et al. 2016; Tullberg et al. 2018). Prevention of soil compaction will likely have ***small co-benefits*** for adaptation (Section 6.4.2.1), but can deliver ***large co-benefits*** for prevention and reversal of desertification and

large co-benefits for prevention and reversal of land degradation, since soil compaction is a main driver of both desertification and land degradation (FAO and ITPS 2015). Prevention of compaction delivers ***moderate co-benefits*** for food security by helping to close yield gaps in rainfed crops (Anderson and Peters 2016). Implementation costs are not high since compaction avoidance technologies require less fuel and provide a win–win strategy for farmers and the environment (Chamen et al. 2015). There are likely to be ***few adverse side-effects***. Although both compaction process and remediation technologies are well-known, barriers include biophysical (some soils are prone to compaction), technological (e.g., few decision support systems for implementation of precision management of traffic compaction) and educational (knowledge gaps; Antille et al. 2016).

6.5.1.12 Fire management

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Fire management									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Fire management provides ***moderate co-benefits*** for climate mitigation by reduced size, severity, and frequency of wildfires (Tacconi 2016; Arora and Melton, 2018), ***moderate co-benefits*** for climate adaptation by reducing mortality attributable to landscape fire smoke exposure (Doerr and Santin, 2016; Johnston et al., 2012; Shannon et al., 2016), ***large co-benefits*** for prevention or reversal of desertification by increased control of wildfires and long-term maintenance of tree stock density to protect against soil erosion (Neary 2009; Arora and Melton, 2018) and ***large co-benefits*** for prevention or reversal of land degradation by stabilising forest ecosystems (Neary 2009; Arora and Melton, 2018). Forest fire management can guarantee forest product availability and prevention of fire expansion to agricultural land, so it has ***large co-benefits*** also for food security (FAO 2015). Barriers to implementation include biophysical (e.g., susceptibility to climate and other unpredicted events; Hurteau et al. 2014; or steep or remote areas to its application; North et al. 2015), technological, institutional (e.g., lacks of social or political acceptance; Freeman et al. 2017) and educational (e.g., poor knowledge of best practices, liability issues, casualty risks and little tolerance for management errors; North et al. 2015). Technologies for fire management exist, but the cost of its implementation is relatively moderate, since it requires constant maintenance (North et al. 2015), and can be excessive for some local communities.

6.5.1.13 Management of landslides and natural hazards

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Management of landslides and natural hazards									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

The prevention and management of landslides and natural hazards has ***small co-benefits*** for mitigation, because of the limited impact on GHG emissions and eventual preservation of topsoil carbon stores, but ***large co-benefits*** for adaptation, since the response options provide structural/physical adaptations to climate change (IPCC AR5 WG2, Chapter 14; Noble et al. 2014). In the same way ***small co-benefits*** could be realised for desertification control (Chapter 3; Section 6.4.3.1), but there are ***large co-benefits*** for land degradation, since landslides and natural hazards are among the most severe degradation processes (Chapter 4; Section 6.4.4.1; FAO and ITPS 2015). In countries in which mountain slopes are cropped for food crops, such as the case of Pacific Islands (Campbell 2015), the management and prevention of landslides can deliver ***moderate co-benefits*** for food security. There are few ***adverse side effects*** from measures to reduce the risk of landslides and natural hazards. Most of the deaths caused due to different disasters have occurred in developing countries, in which poverty, poor education and health facilities and other aspects of human population increase exposure and high levels of vulnerability and risk (Mal et al. 2018). In the tropics, the most cited barriers for implementing landslide risk reduction measures are scientific and political in nature, and the ratio of implemented versus recommended landslide risk reduction measures is low for most landslide risk reduction components (Maes et al. 2017). The implementation of practices for management of landslides and natural hazards is based on engineering works and more resilient cropping systems (Noble et al. 2014; Gill and Malamud 2017), which are is often limited by their high costs, as well as biophysical, technological and educational barriers.

6.5.1.14 Ecosystem-based adaptation

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Ecosystem-based adaptation									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Ecosystem based Adaptation (EbA) has ***large co-benefits*** for mitigation, due to protection and restoration of existing ecosystems which may serve as carbon sinks (forests, mangroves, grasslands, wetlands, etc.) (Section 6.4.1.1; Jones et al. 2012; Griscom et al., 2017). EbA offers ***large co-benefits*** for adaptation, as by its very name, EbA involves the use of ecosystems to increase adaptive capacity (Section 6.4.2.1). EbA is often based on local, available and renewable inputs, and is asserted to be more cost-effective than other approaches to adaptation (such as hard infrastructure) (Jones et al. 2012; Ojea 2015), as well as being more flexible, less path dependent and potentially reversible (van Wesenbeeck et al. 2014; Jones et al. 2012). EbA is expected to have ***small co-benefits*** (largely unquantified; Chapter 3; Section 6.4.3.1) for prevention and reversal of desertification, and has ***large co-benefits*** for prevention and reversal of land degradation, as EbA involves ecologically-based management practices known to reduce degradation (Chapter 4; Section 6.4.4.1; Vignola et al. 2015). EbA also promises ***large co-benefits*** for food security and has been proposed as a means to improve food security (Section 6.4.5.1; Munang et al., 2015). Potential ***adverse side-effects*** from EbA include potentially lower yields in agricultural systems adopting EbA and trade-offs between long term improvements and short-term labour and other costs (Vignola et al. 2015). Barriers to EbA include lack of information about what roles ecosystems play, trade-offs for farmers in terms of labor and benefits, and challenges in scalability and governance as EbA is challenging for siloed policy systems (Scarano 2017; Vignola et al. 2013; Ojea 2015; Burch et al. 2014).

6.5.1.15 Reduced deforestation and forest degradation

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Reduced deforestation									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Reduced deforestation and forest degradation provides ***large co-benefits*** for climate mitigation by maintaining the carbon sequestration in forest ecosystems (Chapter 2; Section 6.4.1.1; Pan et al. 2011a). There are no quantified global estimates of the likely impacts on adaptation, prevention or reversal of desertification, prevention of land degradation or food security. The carbon stock in the forest is prone to both reversibility and saturation. The reduced deforestation practices have relatively moderate costs, but it requires transaction and administration costs (Overmars et al. 2014; Kindermann et al. 2008a). Barriers to its implementation include biophysical (e.g., susceptibility to climate and other unpredicted events; Ellison et al. 2017), institutional (e.g., land tenure, economic disincentives and transaction costs; Kindermann et al. 2008) , educational (e.g., little information available in some regions) and cultural (different realities, e.g., small holder versus industrial production).

6.5.1.16 Management of pollution including acidification

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Management of pollution including acidification									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Measures to reduce emissions of Short-Lived Climate Pollutants (SLCPs) can slow projected global mean warming (Shindell et al., 2017) so early management of SLCPs would be expected to deliver benefits for mitigation with respect to providing 0.5°C cooling by 2050 (Shindell et al., 2012). On the other hand, reduced reactive nitrogen deposition could decrease terrestrial carbon uptake significantly, meaning that the impacts on climate mitigation range from ***large co-benefits*** to ***large adverse side-effects*** (Section 6.4.1.1). Since controlling PM2.5 and ozone improves human health, it would provide ***moderate co-benefits*** for adaptation (Section 6.4.2.1; Anenberg et al., 2012). Acid deposition is a significant driver of land degradation (Smith et al. 2015), so its management would be expected to deliver ***moderate co-benefits*** for prevention and reversal of desertification where salinisation, pollution, and acidification are a stressor (Section 6.4.3.1; Oldeman et al., 1991) and ***moderate co-benefits*** for prevention and reversal of land degradation (Section 6.4.4.1; Oldeman et al., 1991: Smith et al. 2015). Since ozone is harmful to crops, measures to reduce air pollution would be expected to increase crop production, thereby producing ***large co-benefits*** for food security (Section 6.4.5.1; Shindell et al., 2012). There are ***some adverse side-effects***, though atmospheric nitrogen deposition can be an important source of nitrogen in low input agriculture and forestry, so reducing emissions could have negative impacts on crop and tree growth (Bala et al., 2013). Barriers to implementation are mainly biophysical (since air pollution is transboundary, so sources are often far distant from the site of impact; Begum et al., 2011) technological (e.g., lack of technology to inject fertilisers below ground to prevent ammonia emissions; Shah et al., 2018), institutional (e.g., poor regulation and enforcement of environmental regulations; Yamineva and Romppanen, 2017), cost and behavioural (e.g., high cost to expand use of energy-efficient devices to reduce emission of pollutants from household and heating sectors in developing countries; WMO 2015).

6.5.1.17 Management of invasive species

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Management of invasive species / encroachment									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

There is no literature that assesses the global potential of management of invasive species on mitigation, adaptation, prevention or reversal of desertification or land degradation or on food security (Section 6.4.1.1, 6.4.2.1, 6.4.3.1, 6.4.4.1 and 6.4.5.1). The resilience of rural livelihoods can also be improved since manual clearance can create job opportunities for the local population, local populations can breed indigenous plants and secure investments in nurseries. In some places, the replanting of the original species is tied with education and public campaigns to ensure ownership and future protection from introduction of non-native species. In this respect, the co-benefits of manual clearance of invasive species are higher than introduction of natural enemies of the invasive species. There are ***no adverse side-effects*** though natural enemies need to be well targeted so that they do not present similar problems to the invasive species. Barriers are partly biophysical, since restoration programmes can take a long time, and in the case of natural enemies can be technological (Dresner et al. 2015). Education can be a barrier, where populations are unaware of the damage caused by the invasive species, and institution barriers occur where agricultural extension and advice services are poorly developed. Cultural / behavioural barriers are likely to be small.

6.5.1.18 Reforestation

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Reforestation									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Reforestation provides ***large co-benefits*** for climate mitigation by rebuilding the carbon stocks in forest ecosystems, although decreases in surface albedo can reduce the net climate benefits in areas affected by seasonal snow cover (Chapter 2; Section 6.4.1.1; Sonntag et al. 2016; Mahmood et al. 2014). There are ***large co-benefits*** for climate adaptation by increasing provision of forest Nature's Contributions to People (Section 6.4.2.1; Locatelli et al. 2011; Reyer et al. 2009), ***large co-benefits*** for prevention or reversal of desertification by restoring forest ecosystems in suitable areas (Chapter 3; Section 6.4.3.1; Idris Medugu et al. 2010b; Salvati et al. 2014), and ***large co-benefits*** for reversal of land degradation through reestablishment of perennial vegetation (Chapter 4; Section 6.4.4.1; Ellison et al. 2017). However, there are ***large adverse side-effects*** for food security due to potential land competition with food production (Chapter 5; Section 6.4.5.1; Frank et al. 2017). The carbon sink provided by forest both saturates and is reversible. The reforestation practices have relatively moderate costs (Strengers et al. 2008). Barriers to its implementation include biophysical (e.g. availability of native species seedlings for planting), institutional, educational (e.g., low genetic diversity of planted forests) and cultural (e.g., care of forest cultures).

6.5.1.19 Restoration and avoided conversion of coastal wetlands

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Restoration and avoid conversion of coastal wetlands									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Coastal wetland restoration provides ***moderate co-benefits*** for climate mitigation, with avoided coastal wetland impacts and coastal wetland restoration estimated to deliver 0.3 and 0.8 (total 1.1) $GtCO_2\ yr^{-1}$, respectively, by 2030 (Section 6.4.4.1; Griscom et al. 2017). Coastal wetland restoration may also provide ***large co-benefits*** for climate adaptation, e.g. by providing a natural defence against coastal flooding and storm surges by dissipating wave energy, reducing erosion and by helping to stabilise shore sediments – potentially contributing to flood protection to hundreds of millions of people (Section 6.4.2.1). There are likely ***no co-benefits*** (nor adverse side effects) of coastal wetland restoration for prevention of desertification (Section 6.4.3.1). Since large areas of global coastal wetlands are degraded (Lotze et al. 2006; Griscom et al. 2017a), restoration provides ***moderate co-benefits*** for preventing and reversing land degradation (Section 6.4.4.1). Since large areas of converted coastal wetlands are used for food production (e.g., mangroves converted for aquaculture; Naylor et al. 2000), restoration could displace food production and damage local food supply (Section 6.4.4.1), potentially leading to a ***small adverse side-effect*** for global food security. The carbon sink associated with coastal wetland restoration is reversible, though saturation is likely to take many decades (Griscom et al. 2017a). Costs for coastal wetland restoration projects vary, but they can be cost-effective at scale (Erwin 2009). Barriers to implementation include biophysical (e.g., loss of large predators, herbivores, spawning and nursery habitat; (Lotze et al. 2006), can be institutional in some regions (e.g., poor governance of wetland use in some regions; (Lotze et al. 2006), and educational (e.g., lack of knowledge of impact of wetland conversion), though technological and cultural / behavioural barriers are likely to be small compared to other barriers.

6.5.1.20 Biochar

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Biochar									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Use of biochar as a soil amendment provides ***large co-benefits*** for climate mitigation (Chapter 2; Section 6.4.4.1; Smith, 2016; Fuss et al., 2018; SR1.5). There are no global estimates of the impact of biochar on climate adaptation (Section 6.4.2.1) or on prevention or reversal of desertification (Section 6.4.3.1). There are ***small co-benefits*** for prevention or reversal of land degradation, in both cases by improving water holding capacity, improving nutrient use efficiency, managing heavy metal pollution and other co-benefits (Section 4.9.5.2; Section 6.4.4.1; Sohi, 2012). Though biochar can provide ***small co-benefits*** got food production where applied to cropland by improving yield in the tropics (but less so in temperate regions; Jeffery et al., 2017), the additional pressure on land if large quantities of biomass are required as feedstock for biochar production, would likely lead to ***large adverse side-effects*** on food security (Section 6.4.5.1). Depending on the scale of implementation, the land requirement for biomass feedstock (Smith, 2016) could be significant and lead to a potentially ***large adverse side-effect***, though there are likely to be ***few other adverse side-effects***. The biochar carbon sink is thought to be less reversible than soil organic matter sinks (Smith, 2016), though there is mixed evidence about its residence time (Sohi, 2012). The stability is known to be determined by feedstock and pyrolysis conditions, and the soil to which it is applied (Chapter 4). The biochar sink would also be expected to be less susceptible to saturation (Sohi, 2012). 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 (Shackley et al. 2011; Meyer et al., 2011; Dickinson et al., 2014). With no market for biochar, cost can be a barrier (Chapter 4). Barriers to implementation include biophysical (e.g., land available for biomass production; (Woolf et al. 2010), technological (e.g., feedstock and pyrolysis temperature have large impacts on biochar properties; ref), can be institutional in some regions (e.g., lack of quality standards; Guo et al., 2016), educational (e.g., low awareness among end users; Guo et al., 2016), and cultural / behavioural (Guo et al., 2016).

6.5.1.21 Restoration and avoided conversion of peatlands

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Restoration and avoid conversion of peatlands									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Peatland restoration provides ***moderate co-benefits*** for climate mitigation, with avoided peat impacts and peat restoration estimated to deliver 0.8 and 0.8 (total 1.5) $GtCO_2\ yr^{-1}$, respectively, by 2030 (Section 6.4.1.1; Griscom et al. 2017), though there could be a temporary increase in methane emissions after restoration (Jauhiainen et al. 2008). It may also provide ***some co-benefits*** for climate adaptation globally by regulating water flow and preventing downstream flooding (Section 6.4.2.1; Munang et al. 2014), though the potential has not been quantified globally (Section 6.4.2.1). There are likely ***no co-benefits*** (nor adverse side effects) of peatland restoration for prevention of desertification (Section 6.4.3.1), as peatlands occur in wet areas and deserts in arid areas so they are not connected. Considering that large areas of global peatlands are degraded (Griscom et al., 2017), peatland restoration provides ***moderate co-benefits*** for preventing and reversing land degradation (Section 6.4.4.1). 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 (Section 6.4.4.1), potentially leading to a ***moderate adverse side-effect*** for food security globally, though the impact may be more significant in the affected areas. Avoided emissions from peatlands are permanent upon restoration, but the carbon sink is reversible (Griscom et al. 2017a). Since peatlands continue to accumulate carbon over hundreds or thousands of years under suitable conditions, unlike mineral soils, the carbon sink does not saturate (Dommain et al. 2014). Direct CO_2 removal costs for wetland restoration range from USD 10–100/tCO_2 (Worrall et al. 2009), suggesting potential low-cost options for projects. Barriers to implementation include biophysical (e.g., site inaccessibility; Bonn et al. 2014), can be institutional in some regions (e.g., lack of inputs; Bonn et al. 2014), and educational (e.g., lack of skilled labour; Bonn et al. 2014), though technological and cultural / behavioural barriers are likely to be small compared to other barriers.

6.5.1.22 Afforestation

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Afforestation									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Afforestation provides ***large co-benefits*** for climate change mitigation (Chapter 2; Section 6.4.2.1), especially if occurring in the tropics and in areas that are not significantly affected by seasonal snow cover. There are ***large co-benefits*** for climate adaptation (Chapter 2; Section 6.4.2.1; Kongsager et al. 2016; Reyer et al. 2009), ***large co-benefits*** for prevention or reversal of desertification by providing perennial vegetation in arid areas (Chapter 3; Section 6.4.3.1; Idris Medugu et al. 2010a; Salvati et al. 2014), ***large co-benefits*** for prevention or reversal of land degradation by stabilising soils through perennial vegetation (Chapter 4; Section 6.4.4.1; Lal 2001). The competition for land between afforestation/reforestation and agricultural production is a potential ***large adverse side-effect*** (Boysen et al. 2017a,b; Kreidenweis et al. 2016a; Smith et al. 2013)Afforestation also has ***large co-benefits*** with a number of Nature's Contributions to People, as it increases carbon storage in biomass and soil organic matter, reduced erosion and improved regulation of flooding, improved water quality and increasing habitat provision to enhance biodiversity (Whitehead 2011). Afforestation also has the potential to filter out sediment and excess nutrients before entering streams (Newbold et al. 2010). Planting monocultures of non-native or native improved-growth species will likely yield greater carbon accumulation rates but ***adverse side-effect*** in terms of biodiversity loss. Under poor management, afforestation can result in a reduction of biodiversity in the local ecosystem, with introduction of potentially invasive and non-native species, reduced stream flow and loss of agricultural revenue (Cunningham et al. 2015). The carbon sink provided by afforestation both saturates and is reversible. The reduced deforestation practices have relatively low cost (Kreidenweis et al. 2016a). Barriers to its implementation include biophysical, technological (e.g., achieve necessary rates of yields; Kreidenweis et al. 2016), institutional (e.g., policy makers commitment; (Idris Medugu et al. 2010c), educational and cultural.

6.5.1.23 Avoidance of conversion of grassland to cropland

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Avoidance of conversion of grassland to cropland									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Avoidance of conversion of grassland to cropland could provide ***moderate co-benefits*** for climate mitigation by retaining soil carbon stocks that might otherwise be lost. Historical losses of soil carbon have been on the order of 500 $GtCO_2$ (Sanderman et al. 2017). Mean annual global cropland conversion rates (1961–2003) have been 0.36% per year (Krause et al. 2017), i.e. around 4.7 Mha yr^{-1} – so preventing conversion could potentially save significant emissions of CO_2. There is no literature to assess the co-benefits for adaptation. In areas where shifting to arable use can provide high-yielding grain crops, there could be ***small co-benefits*** for prevention or reversal of desertification by stabilising soils in arid areas (Chapter 3; Section 6.4.3.1), and ***small co-benefits*** for prevention or reversal of land degradation through the same mechanism (Chapter 4; Section 6.4.4.1). There are likely to be ***moderate adverse side-effects*** for food security, since conversion of grassland to cropland usually occurs to remedy food security, and much more land is required to produce human food from livestock products on grassland than from crops on cropland (Chapter 5; Section 6.4.5.1; de Ruiter et al. 2017; Clark and Tilman 2017). The soil carbon sink both saturates and is reversible (see section on increasing soil organic matter content; Smith 2013), though this response option is about protecting existing stocks rather than increasing them. Avoiding conversion is low cost, but there may be significant opportunity costs associated with foregone production of crops. Since the response option involves not cultivating a current grassland, there are likely to be few biophysical or technological barriers, but there could be institutional barriers in some regions (e.g., poor governance to prevent conversion), and educational (e.g., poor knowledge of the impacts of ploughing grasslands, and cultural / behavioural (e.g., strong cultural importance of crop production in some communities. Avoidance of grassland conversion to cropland also avoids risks for the livelihoods of pastoralists in extensively managed rangelands.

6.5.1.24 Enhanced weathering of minerals

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Enhanced weathering of minerals									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Enhanced mineral weathering provides ***large co-benefits*** for climate mitigation, with a global mitigation potential in the region of about 0.7–3.7 $GtCO_2$ yr^{-1} (Section 6.4.1.1; Lenton 2010; Smith et al. 2016a; Taylor et al. 2016). There is no literature to assess the global impacts of enhanced mineral weathering on adaptation (Section 6.4.2.1) nor on desertification (Section 6.4.3.1). There would be expected to be small positive impacts on prevention or reversal of desertification. Since ground minerals can increase pH (Section 6.4.4.1; Taylor et al. 2016), there could be ***small co-benefits*** for prevention and reversal of land degradation, where acidification is the driver of degradation (Taylor et al. 2016b). Though there may be co-benefits for food production (Section 6.4.5.1; Beerling et al., 2017), these have not been quantified globally. 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, so there are likely to be ***small adverse-side effects globally***. Permanence is not an issue of the timescales of relevance since the CO_2 absorbed from the atmosphere is mineralised. The main costs (and large energy input) is in the mining and comminution of the minerals (Renforth et al. 2012), with higher total costs compared to low cost. Land management options (Smith et al. 2016a). Barriers to implementation include biophysical (e.g., limited and inaccessible mineral formations; Renforth et al. 2012), institutional in some regions (e.g., lack of infrastructure for this new technology; Taylor et al. 2016), technological (high energy costs of comminution; Smith et al. 2016a) and educational (e.g., lack of knowledge of how to use these new materials in agriculture). Cultural barriers could occur in some regions, for example, due to minerals lying under undisturbed natural areas where mining might generate public acceptance issues (e.g., Renforth et al. 2012).

6.5.1.25 Bioenergy and BECCS

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Bioenergy and BECCS									

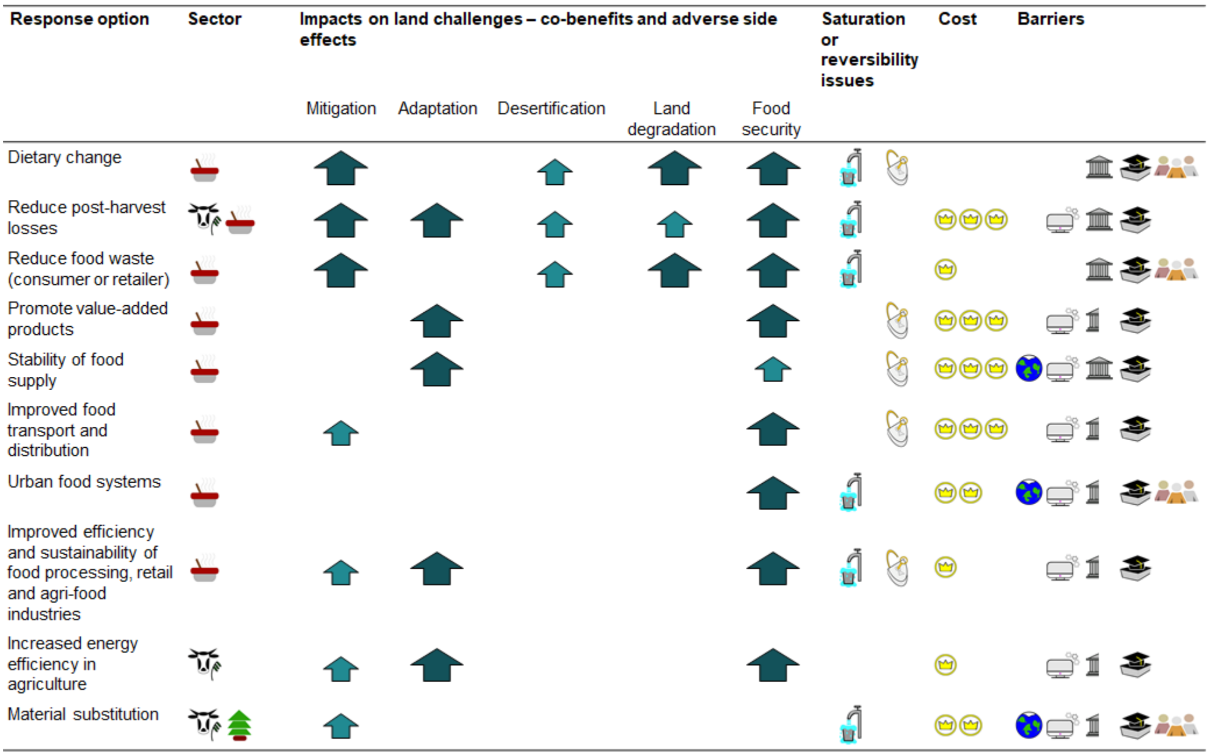
* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

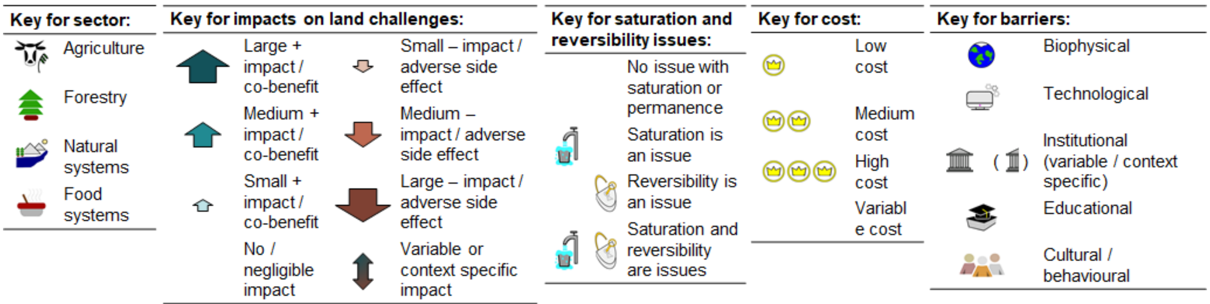
Large-scale use of bioenergy and BECCS provides ***large co-benefits*** for climate mitigation (Section 6.4.1.1), and ***small adverse side-effects*** on adaptation (Section 6.4.2.1). Large scale bioenergy and BECCS could significantly increase pressure on land, meaning potentially ***moderate adverse side-effects*** on desertification (Section 6.4.3.1) and ***large adverse side-effects*** on land degradation (Section 6.4.4.1). Increased competition for land is also expected to lead to ***large adverse side-effects*** for food security (Section 6.4.5.1). The sign and magnitude of the effects of bioenergy and BECCS, however, depends on the scale of deployment, the type of bioenergy feedstock, and where bioenergy is grown (see Section 6.3.1.25). 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 (Section 6.5.4). The main barriers are biophysical, technological, institutional and cultural (IPCC SR1.5; Chapter 7). In terms of technological barriers, while there are a few small BECCS demonstration facilities, BECCS has not been implemented at scale (Kemper 2015). Cultural barriers include social acceptance (Sanchez and Kammen 2016) with CCS facing concerns of safety and environmental issues and bioenergy facing additional scrutiny because of competition for land and water. Institutional barriers include governance issues (Vaughan and Letters). In terms of economic barriers, while most estimates indicate the cost of BECCS as less than $200/t CO_2, there is significant uncertainty (IPCC SR1.5).

6.5.2 Integrative response options based on value chain management

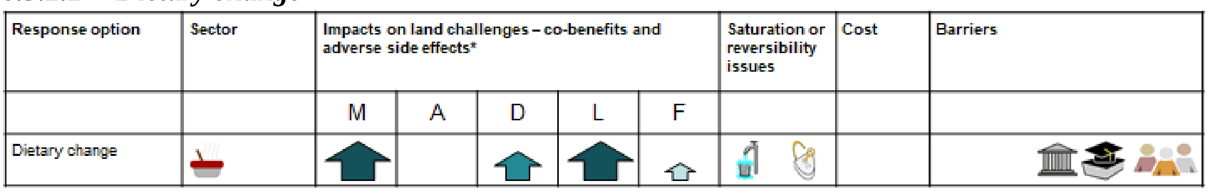
The co-benefits, adverse side effects, permanence/saturation issues, costs and barriers of response options based on value chain interventions are summarised below in Table 6.20. The sections below deal with each response option.

Table 6.20 Summary of co-benefits, adverse side effects, permanence/saturation issues, costs and barriers of response options based on value chain management to address land challenges





6.5.2.1 *Dietary change*



* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

A transition to sustainable healthy diets would provide ***large co-benefits*** for climate mitigation (Chapter 5; Section 6.4.2.2), and while it would be expected to help with adaptation, there are no studies providing global quantification (Section 6.4.3.2). There are potentially ***moderate co-benefits*** (due to relatively limited global area) for prevention or reversal of desertification (Section 6.4.3.2), but ***large co-benefits*** for prevention or reversal of land degradation (Section 6.4.4.2). There are also ***large co-***

benefits for food security (Section 6.4.5.2). There are likely to be ***few adverse side-effects*** across the challenges (Bajželj et al. 2014a; Tilman and Clark 2014a; Clark and Tilman 2017a). The main barriers to implementation are cultural / behavioural (e.g., diets are deeply culturally embedded and behaviour change is extremely difficult to effect, even when health benefits are well known; Macdiarmid et al., 2016). Biophysical barriers include poor accessibility of healthy foods such and fruit and vegetables (e.g., Hearn et al. 1998; Lock et al. 2005)and technological barriers include inadequate storage options for e.g. fresh fruit and vegetables. Barriers might also be institutional in some regions (e.g., poorly developed dietary health advice; and educational (e.g., poor knowledge of what constitutes a healthy diet; Wardle et al. 2000).

6.5.2.2 Reduced post-harvest losses

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Reduce post-harvest losses									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Reducing post-harvest losses has ***large co-benefits*** for mitigation (Section 6.4.1.2), though increased use of refrigeration could increase emissions from energy use. Since reduced food losses reduces pressure on the land, there are also ***large co-benefits*** for adaptation (Section 6.4.2.2). There are likely to be ***moderate co-benefits*** for prevention and reversal of desertification (Section 6.4.3.2) and ***moderate co-benefits*** for prevention and reversal of land degradation (Section 6.4.4.2), both through reduced pressure on land. There are ***large co-benefits*** for food security, since most of the 30% of all food wasted globally arises from post-harvest losses in developing countries (Chapter 5; Section 6.4.5.2; Ritzema et al. 2017). There are likely to be ***no adverse side-effects***. Barriers are largely institutional, since solutions may require dismantling and redesigning current food value chains, and technological barriers are lack of low cost storage and preservation technologies. There are few biophysical, educational or cultural barriers, since preventing food loss is a priority in many developing countries.

6.5.2.3 Reduced food waste (consumer or retailer)

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Reduce food waste (consumer or retailer)									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

A reduction in food waste would provide ***large co-benefits*** for mitigation (Section 6.4.1.2), but there are no studies quantifying global adaptation impacts (Section 6.4.2.2). There are ***moderate co-benefits*** for desertification (Section 6.4.3.2), and ***large co-benefits*** for prevention or reversal of land degradation (Section 6.4.4.2), and ***large co-benefits*** for food security due to large post-harvest losses globally (Section 6.4.5.2; Kummu et al., 2012). Reductions in food waste would also deliver ***moderate co-benefits*** for other sustainable development goals, including reducing water scarcity through reductions in irrigation water, reducing pollution through reductions in fertiliser use, and reducing biodiversity loss through reductions in agricultural area and fertiliser use. The main barriers to implementation are cultural / behavioural, economic, and institutional. Specific barriers to reducing consumption 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).

6.5.2.4 *Promotion of value-added products*

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Promote value-added products									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

There are no studies assessing the mitigation potential of promoting value-added products (Section 6.4.1.2), but there are ***large co-benefits*** for climate adaptation 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 (Chapter 5; Section 6.4.2.2; Muller et al. 2017). No studies assess the global potential of promotion of value-added products on desertification (Section 6.4.3.2), or on land degradation (Section 6.4.4.2). Promoting value-added products would deliver ***large co-benefits*** for food security (Chapter 5; Section 6.4.5.2; Tilman and Clark 2014). Diversifying markets and developing value-added products in the food supply system improves food security by increasing its economic performance and revenues to local farmers (Reidsma et al. 2010) and strengthens the capacity of the food production chains to adapt to future markets with more stringent climate regulation and improve income of smallholder farmers, increasing their food security (Murthy and Madhava Naidu 2012). Value-added products may also have positive impact when the overall efficiency of the food supply chain and can create closer and more direct links between producers and consumers. There are likely to be ***few adverse side-effects*** across the challenges (Chapter 3: Section 6.4; Clark and Tilman 2017) except in cases where processing of value-added products lead to higher emissions or demand of resources in the food system. Reversibility could be an issue and while there are low cost options, the implementations can be expensive. Developing technical knowledge and building capacity in value-added processing and logistics systems, targeting smallholder farmers and small and medium enterprises can help to overcome inherent technological and educational barriers. While there are no obvious biophysical or cultural barriers, there are institutional barriers in some contexts (e.g., in low income African, Asian and Latin American countries where challenges associated with food insecurity and climate change vulnerability are more acute) (Ingram et al. 2016). Strengthening Institutional and organisational innovation capacities and value-chain collaboration can enhance the effectiveness of strategies to promote value-added products (Capone et al. 2014).

6.5.2.5 *Stability of food supply*

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Stability of food supply									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

There are no studies assessing the mitigation potential of stability of food supply (Section 6.4.1.2). Food supply stability offers ***large co-benefits*** for adaptation, because when households are faced with negative shocks to food supplies, as may happen with price increases or volatility of production, they may sell other productive assets leading to declines in long term livelihoods (Section 6.4.2.2; Fafchamps et al. 1998). Further, coping with higher food prices associated with food instability reduces income available for other adaptation options, especially for the poor (Haggblade et al. 2017). No studies assess the global potential of ensuring stability of food supply on desertification (Section 6.4.3.2), or on land degradation (Section 6.4.4.2). There are ***moderate co-benefits*** for food security because there are clear links between higher food prices as a result of volatility, leading to lower caloric intake and lower quality diet, eventually leading to increases in child malnutrition in particular, which have affected millions in recent decades (Section 6.4.5.2; Vellakkal et al. 2015; Arndt et al. 2016). Shifts in food availability and stability of food supply, caused in part by export bans and competition with land for biofuels, likely led to the 2007–2008 food price shocks that negatively affected food security for millions around the globe, and particularly in Sub-Saharan Africa (Wodon and Zaman 2010; Haggblade et al. 2017). ***Adverse side-effects*** from food stability policies are likely to be minimal and depend on the particular policies put in place to regulate issues like speculation in futures markets. Barriers to tackling food supply stability include 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).

6.5.2.6 Improved food transport and distribution

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Improved efficiency and sustainability of food processing, retail and agri-food industries									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Improved food transportation and distribution provides ***moderate co-benefits*** for climate mitigation by reducing emissions from transport and distribution (Section 6.4.1.2). There are no studies allowing the impact of improving food transportation and distribution systems on adaptation globally (Section 6.4.2.2). Desertification and land degradation can be exacerbated by poor post-production management practices related to food transport and distribution (Bradford et al. 2018b; Temba et al. 2016; Stathers et al. 2013b; Tirado et al. 2010), though there are no studies to quantify the impacts globally (Sections 6.4.3.2 and 6.4.4.2). Improved storage and distribution systems provide ***large co-benefits*** for food and nutrition security (Section 6.4.5.2). The implementation of innovations related to food transport and distribution can be expensive and while there are no obvious biophysical and cultural/behavioural barriers, there are technological (technological barriers include inadequate storage options, educational and context-specific institutional barriers (e.g., in low income African, Asian and Latin American countries where problems are associated with food loss and institutional and organisational innovation capacities) (Ingram et al. 2016). There are likely to be ***few adverse side-effects*** across the challenges (Bajželj et al. 2014a; Tilman and Clark 2014a; Clark and Tilman 2017a). Technical, organisational and climate communication innovations can improve food storage and distribution in poorer countries and reduce losses to between 1-2% in some cases (Kumar and Kalita 2017b).

6.5.2.7 Urban food systems

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Urban food systems									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

There are no studies to assess the potential of urban food systems to contribute to mitigation, adaptation, desertification and land degradation (Sections 6.4.1.2, 6.4.2.2, 6.4.3.2 and 6.4.4.1), but they can provide ***large co-benefits*** for food security (Chapter 5; Section 6.5.5.2; Chappell et al. 2016). There are likely to be few biophysical, technological or cultural / behavioural barriers to implementing improved urban food systems, though institutional and education barriers could play a role.

6.5.2.8 *Improved efficiency and sustainability of food processing, retail and agri-food industries*

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Improved efficiency and sustainability of food processing, retail and agri-food industries									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Improved efficiency and sustainability of retail and agri-food industries could provide ***moderate co-benefits*** for climate mitigation through reduced energy consumption and climate-friendly foods can deliver significant savings in agri-food GHG emissions (Section 6.4.1.2; Song et al. 2017) by reducing greenhouse gas emissions from transportation (Avetisyan et al. 2014), waste (Porter et al. 2016), and energy use (Mohammadi et al. 2014). There are ***large co-benefits*** for climate adaptation among poor farmers (Section 6.4.2.2). There are no studies available to assess the impact of improved efficiency and sustainability of retail and agri-food industries on desertification (Section 6.4.3.2) or on land degradation (Section 6.4.4.2), though there are ***large co-benefits*** for food security by supporting healthier diets and reducing food loss and waste (Chapter 5; Section 6.4.5.2; Garnett 2011). As result of decreasing costs in information technology, biotechnology, and renewable energy systems, implementation of this response option is relatively inexpensive (Ridoutt et al. 2016). There are likely to be ***few adverse side-effects*** across the challenges (Clark and Tilman 2017a). The implementation of strategies to improve the efficiency and sustainability of retail and agri-food industries can be expensive and while there are no obvious biophysical and cultural/behavioural barriers, there are technological (adoption of specific sustainability instruments and eco-innovation practices, educational and context-specific institutional barriers. 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.

6.5.2.9 *Increased energy efficiency in agriculture*

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Increased energy efficiency in agriculture									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Increased energy efficiency in agriculture delivers ***moderate co-benefits*** for mitigation, when reducing CO_2 emissions by decreasing the use of fossil fuels or energy-intensive products, though the emission reduction is not accounted for under AFOLU (Section 6.4.1.2; Smith et al. 2014; IPCC AR5 WG3 Chapter 11). There are ***large co-benefits*** for climate adaptation among poor farmers (Section 6.4.2.2). There are no studies available to assess the impact of increased energy efficiency in agriculture on desertification (Section 6.4.3.2) or on land degradation (Section 6.4.4.2). There are ***large co-benefits*** for food security, largely by improving efficiency for 2.5 people still using traditional biomass for energy (Chapter 5; Section 6.4.5.2). There are ***no adverse side-effects*** from improving energy efficiency in agriculture. Energy efficiency improvement is very cost effective as it decreases energy costs. There are no biophysical barriers to implementation of energy efficiency measures. The main barriers are technological (e.g., low levels of farm mechanisation), institutional (e.g., energy efficiency in agriculture depends strongly on the technology level; Vlontzos et al. 2014), educational (e.g., poor knowledge of alternative energy sources), and behavioural / cultural (e.g., high levels of repetitive labour, making farming unattractive to the youth, and disproportionally affecting women; Baudron et al. 2015).

6.5.2.10 *Material substitution*

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Material substitution									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Material substitution has the potential for ***moderate co-benefits*** for mitigation, with one study estimating a 14–31% reduction in global CO_2 emissions (Oliver et al. 2014). These measures are unlikely to have any appreciable impact upon adaptation, prevention of desertification or land degradation, or delivery of food security. Neither will they impact appreciably on most Nature's Contributions to People.

6.5.3 Integrative response options based on risk management

The co-benefits, adverse side effects, permanence/saturation issues, costs and barriers of response options based on risk management are summarised below in Table 6.21. The sections below deal with each response option.

Table 6.21 Summary of co-benefits, adverse side effects, permanence/saturation issues, costs and barriers of response options based on risk management to address land challenges

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects					Saturation or reversibility issues	Cost	Barriers
		Mitigation	Adaptation	Desertification	Land degradation	Food security			
Establishing secure land tenure									
Prevention of land grabbing									
Management of urban sprawl									
Livelihood diversification									
Promotion of seed sovereignty									
Early warning systems for disaster risk reduction									
Commercial crop insurance									

Key for sector:
- Agriculture
- Forestry
- Natural systems
- Food systems

Key for impacts on land challenges:
- Large + impact / co-benefit
- Medium + impact / co-benefit
- Small + impact / co-benefit
- No / negligible impact
- Small – impact / adverse side effect
- Medium – impact / adverse side effect
- Large – impact / adverse side effect
- Variable or context specific impact

Key for saturation and reversibility issues:
- No issue with saturation or permanence
- Saturation is an issue
- Reversibility is an issue
- Saturation and reversibility are issues

Key for cost:
- Low cost
- Medium cost
- High cost
- Variable cost

Key for barriers:
- Biophysical
- Technological
- Institutional (variable / context specific)
- Educational
- Cultural / behavioural

6.5.3.1 *Establishing secure land tenure*

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Establishing secure land tenure									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Establishing secure land tenure will likely have ***moderate co-benefits for mitigation,*** namely due to the fact that forest titling programs tend to lead to improved management of forests (Section 6.4.1.3; Nelson et al. 2001; Holland et al. 2017; Blackman et al. 2017). Land tenure security is likely to lead to ***large co-benefits*** for adaptation, as it leads to reduced deforestation and degradation, increasing communities' ability to use forest resources to adapt (Section 6.4.2.3; Suzuki 2012; Balooni et al. 2008; Ceddia et al. 2015; Pacheco et al. 2012). There are no data to assess the impact on desertification (Section 6.4.3.3), but establishing secure land tenure could deliver ***small co-benefits*** for land degradation (Section 6.4.4.3) by securing tenure of indigenous peoples. There are likely to be ***moderate co-benefits*** for food security, as strong land tenure is positively correlated with food production increases (Section 6.4.5.3; Maxwell and Wiebe 1999; Holden and Ghebru 2016; Corsi et al. 2017), although in some cases land formalisation has led to reduced food security for smallholders when they have been pushed to commercialise farming (Pritchard 2013). There are likely ***few adverse side-effects*** from land tenure security measures, although in some cases, formalisation can increase exclusion and has been associated with more confusion over land rights, not less, in some areas where poorly implemented (Broegaard et al. 2017). Barriers to stronger land security include lack of political will and the costs of adopting land formalisation programs (Deininger and Feder 2009).

6.5.3.2 *Prevention of land grabbing*

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Prevention of land grabbing									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Preventing land grabbing has ***small co-benefits for mitigation,*** namely due to avoiding conversion of forests to agriculture and for biofuels. Because many land investments in African countries in particular exceed the documented cultivable land area for the country, forest, wetlands and grasslands have likely been converted, leading to increased GHG emissions (Section 6.4.1.3;(D'Odorico et al. 2017; Balehegn 2015a). There are no studies quantifying how prevention of land grabbing will affect adaptation (Section 6.4.2.3). Preventing land grabbing can also deliver ***small co-benefits*** for prevention and reversal of desertification (Section 6.4.3.3) though the global impact is difficult to quantify, and since land grabs have occurred on nearly 45 Mha of land, likely impacting tens of millions of people, prevention of land grabbing could provide ***moderate co-benefits*** for prevention and reversal of land degradation, as many large-scale investments intensify unsustainable lands uses, leading to soil degradation (Section 6.4.4.3; Friis and Nielsen 2016; Balehegn 2015). There are ***moderate co-benefits*** for food security, with 12 million people already having been affedted by land grabbing (Section 6.4.5.3; (Adnan 2013; Davis et al. 2014). There are likely ***no adverse side-effects*** from preventing land grabbing measures. Barriers to policies against land grabbing include agribusiness opposition, as they are the main funders of such investments, and lack of political will to enact policies to reduce agricultural investments among poor country governments (The World Bank 2011).

6.5.3.3 Management of urban sprawl

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Management of urban sprawl									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

There are no studies assessing the mitigation potential of managing urban sprawl (Section 6.4.1.3). Managing urban expansion offers ***moderate co-benefits*** for adaptation (Section 6.4.2.3) which is poorly quantified globally, but likely to affect many millions of people. There are ***small co-benefits*** for prevention and reversal of desertification (e.g., 0.5 Mha at risk from urban sprawl in Spain alone; Section 6.4.3.3) and ***small co-benefits*** for prevention and reversal of land degradation (e.g., China alone has 20 Mha of land degraded by urban sprawl; Section 6.4.4.3). There are likely to be ***moderate co-benefits*** for food security based on food supply impacts in Eastern China (Chen 2007). This urban sprawl has also resulted in major losses to Nature's Contributions to People from urban conversion (Song and Deng 2015). Specific types of agriculture are often practiced in urban-influenced fringes, such as fruits, vegetables, and poultry and eggs in the US, the loss of which can have an impact on the types of nutritious foods available in urban areas (Francis et al. 2012). There are ***adverse side-effects*** from managing urbanisation may include increased prices for housing if more expensive densification is pursued versus often cheaper extensification. Barriers to policies against urban sprawl include institutional barriers to integrated land use planning and the costs to national governments of restricting or buying back development rights (Tan et al. 2009).

6.5.3.4 Livelihood diversification

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Livelihood diversification									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

There are no studies assessing the mitigation potential of livelihood diversification (Section 6.4.1.3). Diversification offers ***large co-benefits*** for adaptation as it can help households smooth out income fluctuations and provide a broader range of options for the future (Section 6.4.2.3; Thornton and Herrero 2014). Surveys of farmers in climate variable areas find that livelihood diversification is increasingly favoured as an adaptation option (Ahmed and Stepp 2016a). There are no studies assessing the impact of livelihood diversification on desertification (Section 6.4.3.3), but it is likely to provide ***small co-benefits*** for prevention and reversal of land degradation, for example through China's Sloping Land Conversion program to diversify income and reduce degradation, impacting 10 Mha (Liu and Lan 2015 ; Section 6.4.5.3). With at least 700 million smallholders worldwide, many of whom practice diversification, livelihood diversification likely provides ***large co-benefits*** for food security for hundreds of millions of households (Section 6.4.5.3; Morton, 2007). A***dverse side-effects*** from diversification are minimal. Barriers to diversification include the fact that poorer households and female headed households may lack assets to invest in new income streams or have a lack of education about new income sources (Berman et al. 2012; Ahmed and Stepp 2016a; Ngigi et al. 2017).

6.5.3.5 *Promotion of seed sovereignty*

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Promotion of seed sovereignty									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

There are no studies assessing the mitigation potential of promotion of seed sovereignty (Section 6.4.1.3). Promotion of seed sovereignty offers ***large co-benefits*** for adaptation, given that from 60 to 100% of seeds used in various countries of the global South are likely local farmer-bred (non-commercial) seed (Section 6.4.2.3; Louwaars 2002), and moving to use of commercial seed would increase costs considerably for these farmers (Howard 2015). Seed networks and banks protect local agrobiodiversity and landraces, which are important to facilitate adaptation, and can provide crucial lifelines when crop harvests fail (Coomes et al. 2015; van Niekerk and Wynberg 2017; Vasconcelos et al. 2013); for example, problems of seed scarcity and dependence on outside supplies can be overcome by local control over seeds (Reisman 2017). There are no studies assessing the potential of promotion of seed sovereignty to address desertification (Section 6.4.3.3) or land degradation (Section 6.4.4.3). Seed sovereignty provides ***large co-benefits*** for food security because of the increased 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). Women in particular may benefit from seed banks for low value but nutritious crops (Patnaik et al. 2017). The ***adverse side-effects*** from seed sovereignty are minimal. Barriers to seed sovereignty include concerns about equitability in access to seed networks and the difficulty of sustaining such projects when development donors leave (Reisman 2017), and disputes over the intellectual property rights associated with seeds (Timmermann and Robaey 2016).

6.5.3.6 *Early warning systems for disaster risk reduction*

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Early warning systems for disaster risk reduction									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

Early Warning Systems for disaster risk reduction have ***no co-benefits*** for mitigation, as such systems are primarily focused on adaptation. EWS offers ***large co-benefits*** for adaptation; for example, the Famine Early Warning System funded by the USAID has operated across 3 continents since the 1980s, and is praised for the timeliness, quantity, and quality of the warnings provided to countries, focusing on assessing agricultural changes due to climate/weather events, staple food prices, and health (Hillbruner and Moloney 2012). Such information can assist communities and households in adapting to onset conditions. However, concerns have been raised as to how many people are actually reached by such systems; for example, less than 50% of respondents in Bangladesh had heard a cyclone warning before it hit, even though an EWS existed (Mahmud and Prowse 2012). Further, there are concerns that current EWS 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. 2015b), leading to less adaptation potential realised. There are no studies assessing the potential of EWS to address desertification (Section 6.4.3.3) or land degradation (Section 6.4.4.3). There are ***moderate co-benefits*** for food security from EWS when such systems may be focused on warnings to help farmers harvest crops in advance of impending weather events or otherwise make agricultural decisions to prepare for adverse events (Fakhruddin et al. 2015). Surveys with farmers reporting food insecurity from climate impacts have indicated their strong interest in having such EWS (Shisanya and Mafongoya 2016). Additionally, famine early warning systems have been successful in Sahelian Africa to alert authorities to impending food shortages so that food acquisition and transportation from outside the region can begin, potentially helping millions of people (Section 6.4.5.3; Genesio et al. 2011; Hillbruner and Moloney 2012). The ***adverse side-effects*** from EWS are minimal. Barriers to EWS include cost; an early warning system for the 80 most climate vulnerable countries in the world is estimated to cost USD 2 billion over five years to develop (Hallegatte 2012). Institutional and governance barriers such as coordination and synchronisation among levels also effect some EWS (Birkmann et al. 2015b).

6.5.3.7 Commercial crop insurance

Response option	Sector	Impacts on land challenges – co-benefits and adverse side effects*					Saturation or reversibility issues	Cost	Barriers
		M	A	D	L	F			
Commercial crop insurance									

* M = Mitigation, A = Adaptation, D = Desertification, L = Land Degradation and F = Food Security

There is little literature on the impact of commercial crop insurance on mitigatiin, though studies from the US suggest a positive impact (Section 6.4.1.3). Crop insurance offers ***moderate co-benefits*** 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). 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). 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 US have been less likely to adapt to extreme weather events than those not holding insurance (Annan and Schlenker 2015; Section 6.4.2.3). Commercial crop insurance may have ***small adverse side-effects*** for prevention and reversal of desertification though global impacts have not been quantified (Section 6.4.3.3). There may be ***small co-benefits*** for prevention and reversal of land degradation, as evidence suggests that subsidised insurance in particular can increase crop production in marginal lands. There are ***moderate co-benefits*** for food security from crop insurance, as crop insurance has generally lead to (modest) expansions in cultivated land area and increased food production (Claassen et al. 2011; Goodwin et al. 2004a). ***Adverse side-effects*** from crop insurance include water quality problems associated with marginal lands brought into production with greater chemical use due to soil fertility issues (Goodwin and Smith 2003). Barriers to crop insurance include the high costs; few farmers are willing to pay the full commercial cost, which is why most governments subsidise insurance; in the US, this is equivalent to billions of USD every year (Goodwin and Smith 2013).

6.5.4 Impacts of integrated response options on Nature's Contributions to People and the UN Sustainable Development Goals

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 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 provisioning of ecosystem services/nature's contributions to people (see Cross-Chapter Box 7: Ecosystem Services, Chapter 7) can be a useful shorthand for a more comprehensive environmental impact beyond climate and land. Such evaluations are important as there may be unexpected trade-offs with social goals (or potential co-benefits) and impacts on important environmental indicators like water or biodiversity from some of the response options.

In the following sections and tables, we evaluate each response option against 17 SDGs and 18 NCPs. Some of the SDG categories sound 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 to specifically to "positive or negative effects on emissions of greenhouse gases 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" (Diaz 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 A4 to A9 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 'hashed' pattern 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.

6.5.4.1 Impacts of integrated response options on Nature's Contributions to People

Tables 6.22–6.24 summarise the impacts of the response options on NCP provisioning and supply. For the evaluation process, we took the stance that NCPs 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 NCPs, we have also tried to avoid 'indirect' effects – that is a response option might increase household income which then could be invested in habitat-saving actions, or dietary change would lead to conservation of natural areas, which would then led 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 NCPs, which we did not evaluate.[c] Instead, the table focuses as much as we can on *direct* effects only: for example, seed sovereignty policies preserve local land races, which *directly* contribute to 'maintenance of genetic options' for the future. Therefore, this NCP table should be considered 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 (Rodriguez et al 2006), so provisioning of one might lead to less availability of another – for example, use of ecosystems to produce energy through biofuels

[c] 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 lowers 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.

will likely lead to decreases in water availability if monocropped high intensity plantations are used (Gasparaos et al 2011).

Table 6.22 Impacts on Nature's Contributions to People 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 sedime	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 soil organic matter content (and reduced losses)																		
Improved cropland management																		
Improved livestock management																		
Improved grazing land management																		
Increased food productivity																		
Agro-forestry																		
Sustainable forest management																		
Agricultural diversification																		
Management of soil erosion																		
Prevent / reverse soil salinization																		
Prevention of compaction																		
Fire management																		
Management of landslides and natural hazards																		
Ecosystem-based adaptation																		
Reduced deforestation																		
Management of pollution including acidification																		
Management of invasive species / encroachment																		
Reforestation																		
Restoration and avoided conversion of coastal wetlands																		
Biochar																		
Restoration and avoided conversion of peatlands																		
Afforestation																		
Avoidance of conversion of grassland to cropland																		
Enhanced weathering of minerals																		
Bioenergy and BECCS																		

Table 6.23 Impacts on Nature's Contributions to People 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 sedimer	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)																		
Promotion of value-added products																		
Stability of food supply																		
Improved food transport and distribution																		
Urban food systems																		
Improved efficiency and sustainability of food processing, retail and agri-food industries																		
Increased energy efficiency in agriculture																		
Material substitution																		

Table 6.24 Impacts on Nature's Contributions to People 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 sedimer	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
Establishing secure land tenure																		
Prevention of land grabbing																		
Management of urban sprawl																		
Livelihood diversification																		
Promotion of seed sovereignty																		
Early warning systems for disaster risk reduction																		
Commercial crop insurance																		

6.5.4.2 Impacts of integrated response options on the UN Sustainable Development Goals

Tables 6.25–6.27 summarise the impact of the integrated response options on the UN SDGs. 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 SDGs.

However, it should be noted that some SDGs are internally difficult to assess because they contain many targets and we could not evaluate all of them (e.g., SDG 17 is about partnerships, but has targets ranging from foreign aid to debt restructuring to technology transfer to trade openness). Additionally, it should also be noted that some SDGs 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 should be read with caution for that reason. The specific caveats on each of these interactions can be found in the supplementary material tables.

Table 6.25 Impacts on the UN SDGs of integrated response options based on land management

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 Productio	GOAL 13: Climate Action	GOAL 14: Life Below Water	GOAL 15: Life on Land	GOAL 16: Peace and Justice Strong Institutions	GOAL 17: Partnerships to achieve the Goal
Increased soil organic matter content (and reduced losses)																	
Improved cropland management																	
Improved livestock management																	
Improved grazing land management																	
Increased food productivity																	
Agro-forestry																	
Sustainable forest management and forest restoration																	
Agricultural diversification																	
Management of soil erosion																	
Prevent / reverse soil salinization																	
Prevention of compaction																	
Fire management																	
Management of landslides and natural hazards																	
Ecosystem-based adaptation																	
Reduced deforestation																	
Management of pollution including acidification																	
Management of invasive species / encroachment																	
Reforestation																	
Restoration and avoided conversion of coastal wetlands																	
Biochar																	
Restoration and avoided conversion of peatlands																	
Afforestation																	
Avoidance of conversion of grassland to cropland																	
Enhanced weathering of minerals																	
Bioenergy and BECCS																	

Table 6.26 Impacts on the UN SDGs of integrated response options based on value chain interventions

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 Productio	GOAL 13: Climate Action	GOAL 14: Life Below Water	GOAL 15: Life on Land	GOAL 16: Peace and Justice Strong Institutions	GOAL 17: Partnerships to achieve the Goal
Dietary change																	
Reduced post-harvest losses																	
Reduced food waste (consumer or retailer)																	
Promotion of value-added products																	
Stability of food supply																	
Improved food transport and distribution																	
Urban food systems																	
Improved efficiency and sustainability of food processing, retail and agri-food industries																	
Increased energy efficiency in agriculture																	
Material substitution																	

Table 6.27 Impacts on the UN SDGs of integrated response options based on risk management

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 Productio	GOAL 13: Climate Action	GOAL 14: Life Below Water	GOAL 15: Life on Land	GOAL 16: Peace and Justice Strong Institutions	GOAL 17: Partnerships to achieve the Goal
Establishing secure land tenure																	
Prevention of land grabbing																	
Management of urban sprawl																	
Livelihood diversification																	
Promotion of seed sovereignty																	
Early warning systems for disaster risk reduction																	
Commercial crop insurance																	

6.5.5 Opportunities for implementation of Integrative Response Options

6.5.5.1 Where can the response options be applied?

As shown in Section 6.2.3, a large part of the land area is exposed to multiple land challenges, especially in the Villages, Croplands and Rangelands anthromes. Appropriate responses will vary in each anthrome with the local exposure to one or more land challenges. For instance, in croplands exposed to a combination of rapid climate change, land degradation and food insecurity (see Figure 6.4A) responses could be considered as appropriate when delivering co-benefits for climate change adaptation, for land conservation and for food security. As the challenge of climate change mitigation is not local but global, co-benefits for this challenge would also be required for the design of appropriate responses. Moreover, for agricultural (croplands, rangelands, villages) anthromes, any response having a large adverse side-effect on food security at global scale (Table 6.19) should be excluded.

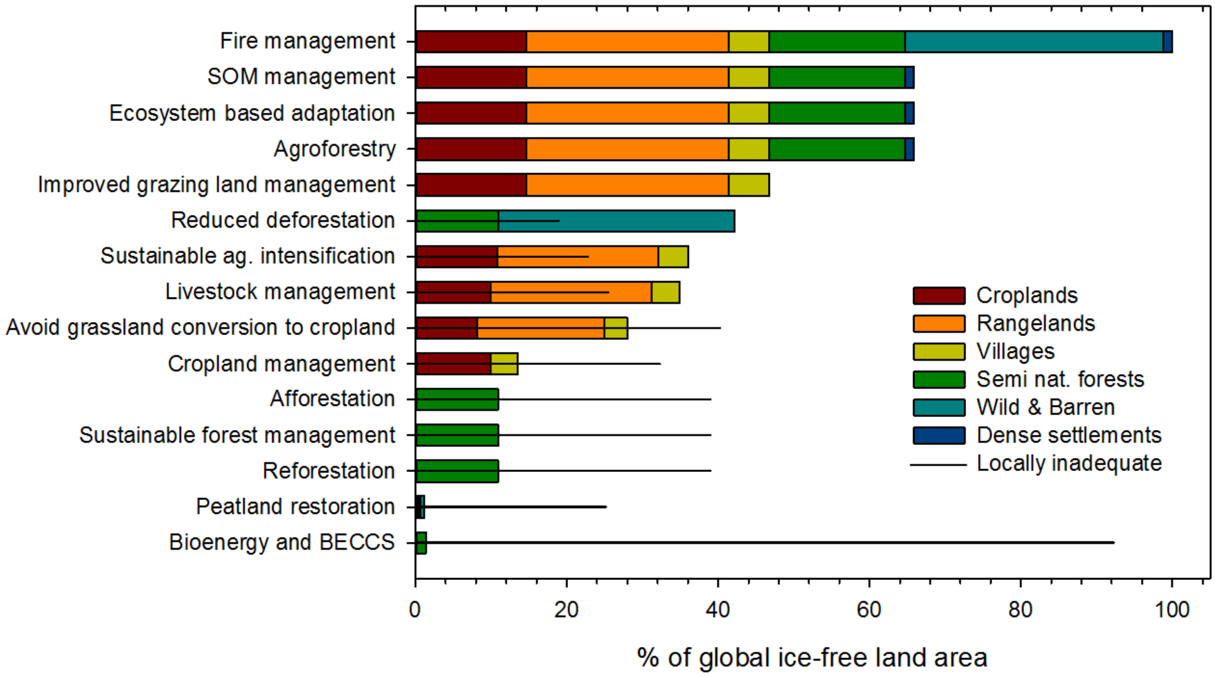


Figure 6.7. Appropriate land management responses and their cumulated global land area distribution by anthrome. Responses are deemed appropriate when combining medium to large co-benefits for pressing local challenges (land degradation and desertification, see Fig. 6.2B; rapid climate change, see Fig. 6.2C; food insecurity, see Fig. 6.2D), medium to large co-benefits for the global mitigation challenge and, for agricultural anthromes, no large adverse side-effect on global food security (see Table 6.19). Horizontal needles show the cumulated percentage land area where response is locally inappropriate across anthromes in which it is used

With the exception of the fire management response, which is appropriate across the 6 anthromes, land management responses are appropriate for between 5 (soil organic matter [SOM] management, ecosystem based adaptation, agroforestry) and one anthrome (bioenergy and BECCS, afforestation, sustainable forest management; reforestation). Responses appropriate for 5 anthromes offer a large potential since they could be deployed over up to 70% of the ice free land area. In contrast, other priority responses have a limited area-based potential due to biophysical constraints (e.g., limited extent of organic soils for peatland restoration) or due to the occurrence of adverse side-effects (e.g., afforestation, reforestation, sustainable forest management and avoiding grassland conversion to croplands present adverse side-effects over 35% or more of total land area). Because of large adverse side effects on food security and land degradation, and small to medium adverse side-effects for climate change adaptation and desertification (see Table 6.19), bioenergy and BECCS, which have strong co-benefits for mitigation, do not appear as an appropriate response over more than 90% of the ice free land area. It is only in semi-natural forests facing no local challenges that this response has only co-benefits (Figure 6.7).

Across anthromes and countries, the mean number of appropriate responses (Figure 6.8 B) declines (P<0.001, Spearman rank order correlation) with the mean number of local land-based challenges (Figure 6.8). Hence, countries facing on average more challenges (Figure 6.8 A) also have fewer options available for deploying appropriate responses with mostly co-benefits and few adverse side-effects. Enabling conditions (see Section 6.2.2.2) for land management responses could partly depend upon three basic dimensions of human development (economics, health and education) which are combined in the Human Development index (HDI, United Nations Development Program, 2018). This country scale composite index (Figure 6.8 C) is negatively correlated (P<0.001, Spearman rank order correlation) with the mean number of land-based challenges per country. Therefore, on a global average, the greater the number of local challenges faced, the fewer the appropriate responses and the lower the enabling conditions (economics, health and education) as seen from the HDI (Figure 6.8).

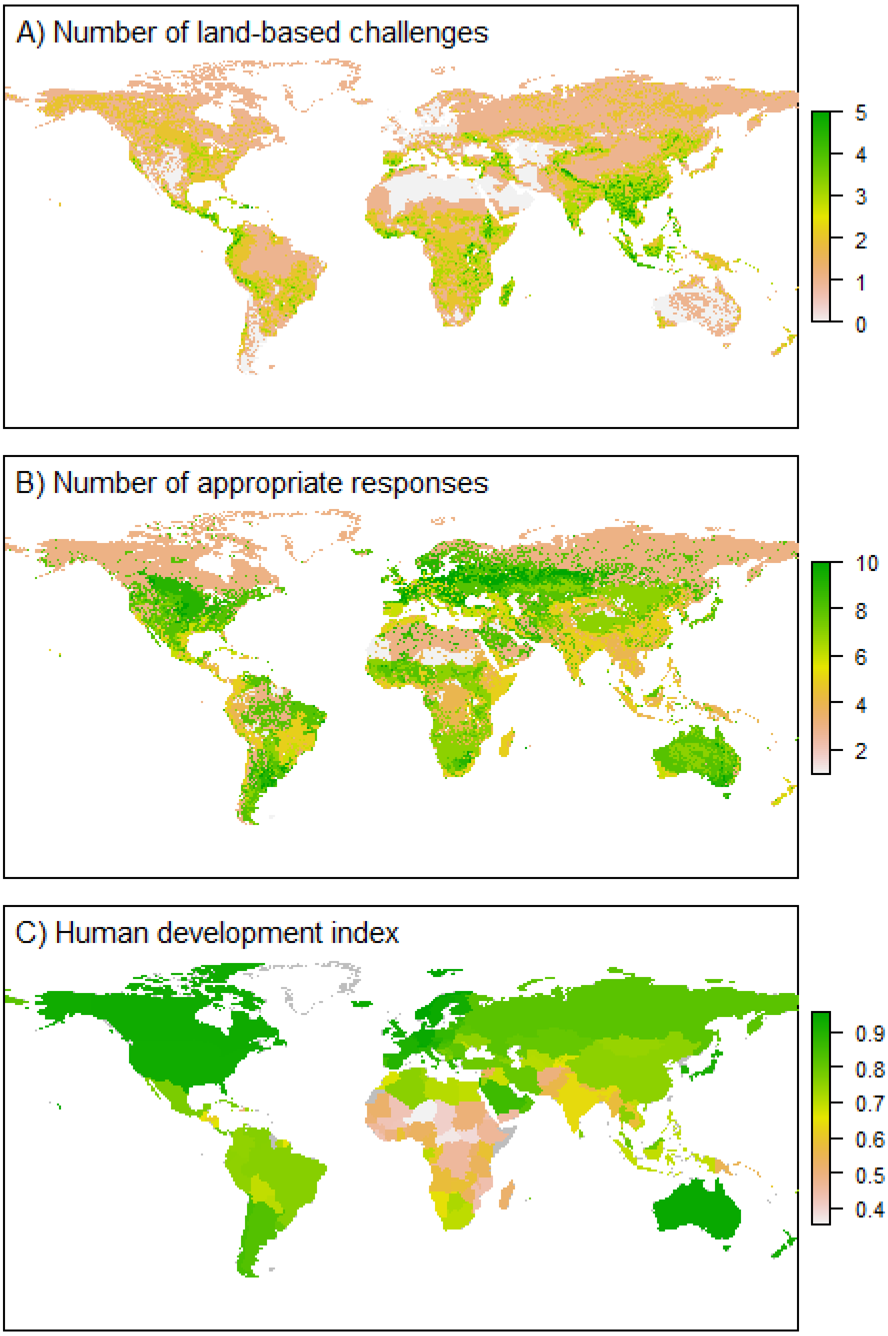


Figure 6.8 Global distributions of: (A) number of local land-based challenges, in addition to the global mitigation challenge; (B) number of appropriate land-management responses (providing medium to large co-benefits and no adverse side-effects); (C) Human Development Index (HDI) by country. In A, land based challenges include land degradation (see Fig. 6.2B); rapid climate change (see Fig. 6.2C); food insecurity (see Fig. 6.2D); threatened biodiversity hotspots (see Fig. 6.2E); groundwater stress affecting cropland and village anthromes (see Fig. 6.2F). In B, appropriate land management responses are those shown in Figure 6.7. In C, the Human Development Index (United Nations Development Programme, 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)

6.5.5.2 Interlinkages and response options in future scenarios

There is a large literature quantifying the effect of various response options in the future. This literature covers a variety of response options and land-based challenges. These studies cover spatial scales ranging from global (Popp et al. 2017; Fujimori et al. 2018) to regional (Calvin et al. 2016; Frank et al. 2015) to country-level (Gao and Bryan 2017b; Pedercini et al. 2018). In this section, we focus on integrated assessment models and agricultural economic models, as these models can quantify interlinkages between response options. Results from bottom-up studies and models (e.g., (Griscom et al. 2017a) are assessed in Section 6.5.3.

Response options in future scenarios:

Approximately one third (15 of 41) of the land-based response options discussed in this chapter are represented in the global models used to develop and analyse future scenarios, either implicitly or explicitly (Table 6.28). 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 N_2O emissions from crop production to carbon prices (most other studies).

However, the literature discussing the effect of these response options on land-based challenges is more limited (Table 6.28). Twenty-four studies articulate the effect of response options on mitigation, with most including bioenergy and BECCS or a combination of reduced deforestation, reforestation, and afforestation. Twenty-three studies discuss the implications of response options on food security, usually using food price as a metric. No studies were identified that quantify the effect of response options on desertification or land degradation within an IAM; however, some studies indirectly use IAMs to quantify these effects by using climate outputs from the RCPs (Huang et al. 2016).

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; 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. 2016a;Humpenöder et al. 2018a)quantifying the effect of including an individual option on a variety of goals.

Table 6.28 Number of Studies Including Specific Response Options (rows) and Quantifying Particular Land Challenges (columns). The second column shows how many models include the individual response option; three computers indicate all models include the option, two computers indicate more than half of all models, one computer indicates less than half. The remaining columns show challenges related to climate change (C), mitigation (M), adaptation (A), desertification (D), land degradation (L), food security (F), and biodiversity/Nature's Contributions to People/sustainable development (O). The number of books indicates number of studies, with 0 (blank), 1–5 (one book), 6–10 (two books), 11–15 (three books), and 16 or more (four books)

Category	Response Option	Models	C	M	A	D	L	F	O
Land Management	Increased soil organic matter content (and reduced losses)	💻		📗				📗	
Land Management	Improved cropland management	💻💻💻		📗📗	📗			📗📗	📗
Land Management	Improved livestock management	💻💻		📗				📗	📗
Land Management	Improved grazing land management	💻💻							
Land Management	(Sustainably) increased food productivity	💻💻💻		📗📗			📗	📗📗	📗📗
Land Management	Agro-forestry								
Land Management	Sustainable forest management	💻💻		📗				📗	📗
Land Management	Agricultural diversification								
Land Management	Management of erosion								
Land Management	Land tenure / ownership								
Land Management	Prevent / reverse soil salinization								
Land Management	Prevention of compaction								
Land Management	Management of urban sprawl								
Land Management	Ecosystem-based adaptation								
Land Management	Reduced deforestation	💻💻	📗	📗📗📗📗				📗📗	📗📗
Land Management	Management of pollution including acidification								
Land Management	Management of invasive species / encroachment								
Land Management	Reforestation	💻💻	📗	📗📗📗			📗	📗📗	📗📗
Land Management	Restoration and avoid conversion of coastal wetlands								
Land Management	Biochar								
Land Management	Peatland restoration								
Land Management	Afforestation	💻💻	📗	📗📗📗				📗📗	📗📗
Land Management	Avoidance of conversion of grassland to cropland	💻		📗				📗	📗
Land Management	Enhanced weathering of minerals								
Land Management	Bioenergy and BECCS	💻💻💻	📗	📗📗📗📗	📗		📗	📗📗📗📗	📗📗
Value Chain Interventions	Dietary change	💻💻		📗📗				📗📗	📗📗
Value Chain Interventions	Reduce post-harvest losses			📗				📗	📗
Value Chain Interventions	Reduce food waste (consumer or retailer)	💻💻		📗				📗	📗
Value Chain Interventions	Promotion of value-added products								
Value Chain Interventions	Stability of food supply								
Value Chain Interventions	Improved food transport and distribution			📗				📗	📗
Value Chain Interventions	Urban food systems								
Value Chain Interventions	Improved efficiency and sustainability of food processing, retail and agri-food industries								
Value Chain Interventions	Increased energy efficiency in agriculture								
Value Chain Interventions	Material substitution	💻							
Risk Management	Prevention of land grabbing								
Risk Management	Fire management	💻		📗					
Risk Management	Management of landslides and natural hazards								
Risk Management	Livelihood diversification								
Risk Management	Promotion of seed sovereignty								
Risk Management	Early warning systems for disaster risk reduction								
Risk Management	Commercial crop insurance								

Interactions and Interlinkages between Response Options:

The effect of response options on desertification, land degradation, food security, biodiversity, and other sustainable development goals depends strongly on which options are included and the extent to which they are deployed. For example, section 6.5.1.23 noted that bioenergy and BECCS has a large mitigation potential but could potentially have adverse side effects for land degradation, food security, and other sustainable development goals. Global modelling studies demonstrate that these effects are dependent on scale. Increased use of bioenergy results in increased mitigation (Figure 6.9, Panel A) and reduced climate change (Figure 6.9, Panel B), but leads to increased cropland expansion (Figure 6.9, Panel C) and increased food prices (Figure 6.9, Panel D). However, these exact relationship between bioenergy deployment and each goal depends a number of other factors, including the specific model used, the underlying socioeconomic scenario, assumptions about technology and resource base, and the inclusion of other response options (Calvin et al. 2014a; Popp et al. 2014, 2017; Kriegler et al. 2014; Clarke and Jiang 2014b)

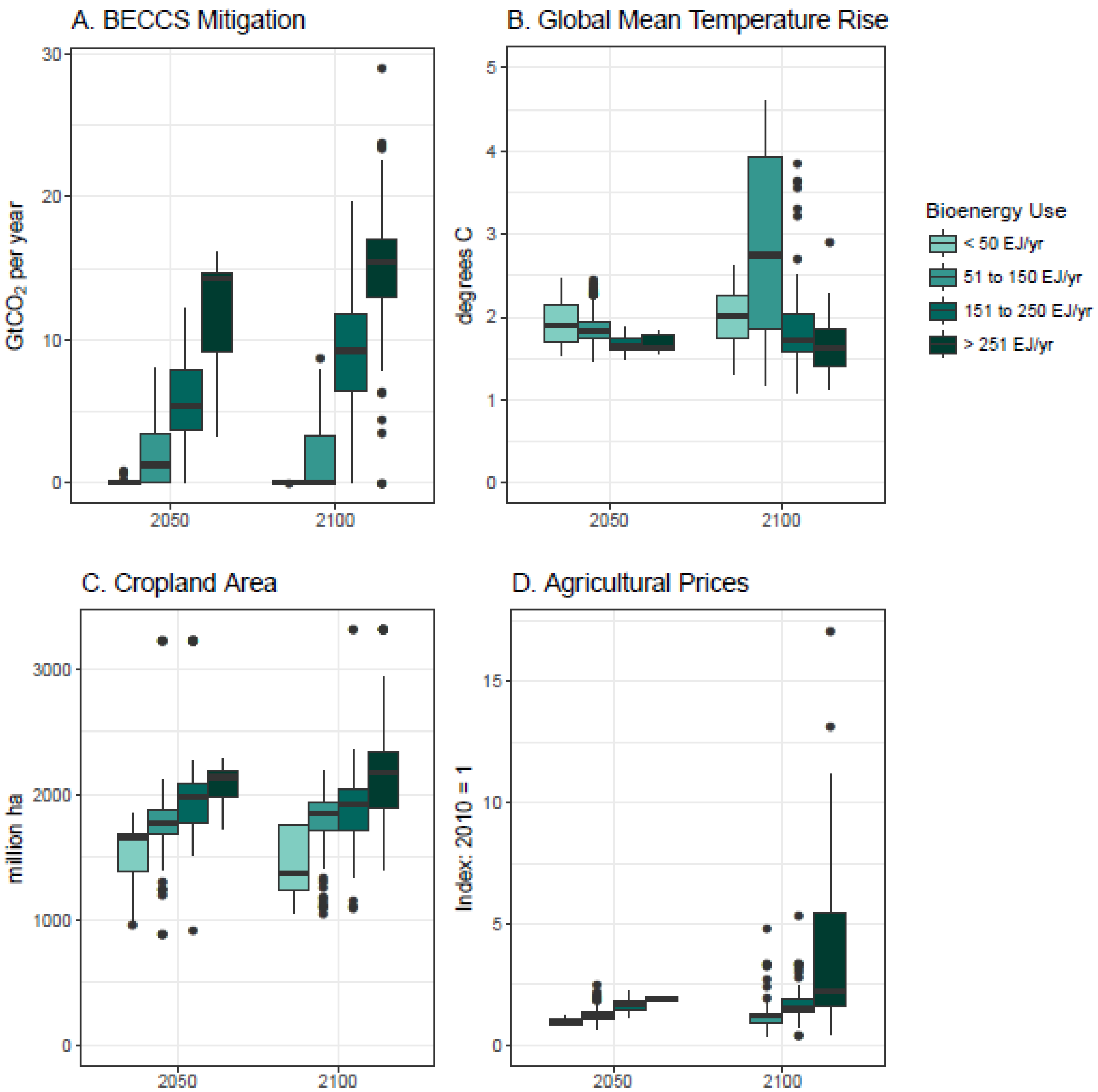


Figure 6.9 Correlation between Bioenergy Use and Other Land Challenges. Panel A shows global carbon sequestration by BECCS. Panel B shows median estimate of global mean temperature rise as calculated by MAGICC6. Panel C shows global cropland area. Panel D shows agricultural prices indexed to 2010. In each panel, data are from the scenario database developed for the Special Report on Climate Change and Land. Data are binned based on the amount of bioenergy used globally in a given year (2050 or 2100). All scenario data that include both bioenergy use and the variable of interest are included in the figure

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 (Table 6.29). Some response options compete for land; therefore, using these combinations of response options can reduce their effectiveness at addressing particular challenges. For example, several studies look at interactions between bioenergy and BECCS, reduced deforestation, reforestation, and afforestation. These studies show that including bioenergy and BECCS reduces afforestation potential (Humpenöder et al. 2014), or conversely adding reduced deforestation, reforestation, and afforestation reduces bioenergy and BECCS potential (Calvin et al. 2014a). The inclusion of reduced deforestation, reforestation, afforestation and/or avoided conversion of grassland to cropland in addition to bioenergy and BECCS can result in increased food prices (Calvin et al. 2014a;

Humpenöder et al. 2018b) and increased climate change due to biophysical effects (Jones et al. 2013), as compared to bioenergy and BECCS alone. However, this combination can result in reduced water consumption (Hejazi et al. 2014c), reduced cropland expansion (Calvin et al. 2014a; Humpenöder et al. 2018b), increased forest cover (Calvin et al. 2014a; Humpenöder et al. 2018b; Wise et al. 2009b)and reduced biodiversity loss (Pereira et al. 2010), as compared to scenarios with bioenergy and BECCS alone.

Other combinations of land response options create synergies, alleviating land pressures. For example, increased food productivity results in reduced cropland expansion and reduced food insecurity for the same level of bioenergy and BECCS production (Humpenöder et al. 2018b; Frank et al. 2017; van Vuuren et al. 2018b). Increased soil organic matter enhances mitigation potential and reduces calorie loss (Frank et al. 2017), compared to scenarios with bioenergy and BECCS alone. Improved cropland management, via increased nitrogen use efficiency, can result in reduced nitrogen losses for the same level of bioenergy and BECCS production (Humpenöder et al. 2018b). The inclusion of increased food productivity, reduced waste, and dietary change together can result increased mitigation, reduced cropland use, reduced water consumption, and reduced fertiliser application (Springmann et al. 2018) . Reducing disturbances (e.g., fire management) in combination with reforestation/afforestation can increase the terrestrial carbon sink, resulting in increased mitigation potential and reduced mitigation cost(Le Page et al. 2013a).

Studies including multiple land response options often find that the combined mitigation potential is not equal to the sum of individual mitigation potential. 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). 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. 2018a).

Table 6.29 Interlinkages and interactions between land-related 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/Nature's Contributions to People/sustainable development (O). Blue up arrows indicate positive interactions (e.g., increased mitigation, reduced cropland area, reduced food prices); red down arrows indicate negative interactions (e.g., increased temperature, increased food prices)

	Additional Response Option	C	M	A	D	L	F	O	Citations
Bioenergy and BECCS	Reduced deforestation, Reforestation, Afforestation	↓	↓			↑	↓	↑	(Jones et al. 2013; Humpenöder et al. 2014; Calvin et al. 2014a; Humpenöder et al. 2018c; Wise et al. 2009a; Hejazi et al. 2014c; Pereira et al. 2010)
	Afforestation and Avoided Conversion of Grassland to Cropland		↓			↑	↓		(Calvin et al. 2014a)
	Increased food productivity		↑			↑	↑	↑	(Humpenöder et al. 2018c; Frank et al. 2017; van Vuuren et al. 2018a)
	Increased soil organic matter		↑						(Frank et al. 2017)
	Improved cropland management							↑	(Humpenöder et al. 2018c)

	Dietary change		↑			↑			(Stehfest et al. 2009; van Vuuren et al. 2018a)
Reduced deforestation, Reforestation, Afforestation +	Bioenergy and BECCS		↓						(Humpenöder et al. 2014)
	Fire management		↑						(Le Page et al. 2013b)
Increased food productivity	Reduced waste + Dietary change		↑			↑	↑	↑	(Springmann et al. 2018b)
	Increased soil organic matter		↑						(Frank et al. 2017)

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 CCS, nuclear energy, energy efficiency and/or renewable energy (van Vuuren et al. 2018; Calvin et al. 2014a; Rose et al. 2014; van Vuuren et al. 2017) 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). Such limitations on bioenergy and BECCS can result in increases in the cost of mitigation (Kriegler et al. 2014; Edmonds et al. 2013) The co-benefits and adverse side-effects of these non-land mitigation options are discussed in SR1.5, Chapter 5.

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) finds increase in bioenergy production due to increases in bioenergy yields, while Calvin et al. (2013) finds declines in bioenergy production and increases in carbon price due to the negative effects of climate on crop yield.

Gaps in the Literature:

As noted previously, 15 of the 41 response options discussed in this chapter are included in the global models described in this section. The included options (e.g., bioenergy and BECCS; reforestation) are some of the largest in terms of large mitigation potential (see Table 6.4). However, some of the options excluded also have large mitigation potential. For example, biochar, agro-forestry, 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. 2017a). Additionally, quantifications of and response options targeting adaptation, land degradation, and desertification are largely excluded from the models; one notable exception is Gao and Bryan (2017b), which does consider land degradation but only in Australia. Finally, while there are a large number of papers examining interactions between bioenergy and BECCS and other response options, the literature examining other combinations of response options is more limited.

6.5.5.3 Moving from response options to policies

Understanding the integrative response options available in a given context requires an understanding of the specificities of social vulnerability, adaptive capacity, and institutional support. Vulnerability often reflects how access to resources are distributed within and among communities, shaped by such factors as “poverty and inequality, marginalisation, food entitlements, access to insurance, and housing quality" (Adger et al. 2004), which are not easily overcome with technical solutions. 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). Conjoining response options to maximise social, climatic and environmental benefits will require framings of such actions as strong pathways to sustainable development (Ayers and Dodman 2010). Chapter 7 discusses in further depth the risks and challenges involved in formulating policy responses that meet these demands for sustainable land management and development outcomes, such as food security, community adaptation and poverty alleviation.

Frequently Asked Questions

FAQ 6.1: What are the approaches to study the interactions between land and climate?

The interactions between climate and land are diverse and complex, because the impacts of climate are often not only local but also remote and take place over long periods of time depending on the presence of forcing agents in the atmosphere. This is expected to have direct effects through the amount of solar radiation that is either absorbed by vegetated surfaces or reflected into space. Therefore, fluxes of heat, gases and water between the land surface and the atmosphere may change, causing changes in temperature and rainfall regimes that can be often observed in remote regions. Land and climate effects take place at the same time and cannot easily be disentangled. There are number of feedback mechanisms between climate and land use and land cover changes, driven by changes in albedo and water vapour flows and associated hydrological changes. Approaches to study the interactions between land and climate range from the study of past climate and land cover changes, to current and recent climate and land use monitoring, in this case based on direct observations and remote sensing, and the use of models and use of scenarios to project possible future outcomes. Land use scenarios are assessed with interdisciplinary methods to predict the impacts of future land use decisions on the climate.

FAQ 6.2: What types of land-based options can help mitigate and adapt to climate change?

Land-based options helping to deliver climate change mitigation are various and differ greatly in their mitigation potential. The most effective ones are those that decrease pressure on land (e.g. by reducing the land needed for food production) and those that increase carbon stores both aboveground (e.g. reduced deforestation and forest degradation, reforestation, agroforestry, fire management) and belowground (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 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). Adaptation options may be planned, such as those implemented at regional, national or municipal level (top-down approaches), or autonomic, such as many technological decisions taken by farmers and local inhabitants (bottom-up and top-down approaches). In any case, their effectiveness depends greatly on the achievement of resilience against climatic extreme events (e.g. floods, droughts, heat waves, etc.).

FAQ 6.3: Which land-based measures to mitigate climate change could also affect desertification, land degradation or food security?

Some options for mitigating climate change are based on increasing carbon stores both above and below ground, so mitigation is usually related to increases in soil organic matter content and increased land cover by perennial vegetation. In any case, 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 so because both 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.

Appendix

Supporting tables. Separate excel sheets will be provided for tables A1-A6.

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