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The impact of interventions in the global land and agri-food sectors on Nature's Contributions to People and the UN Sustainable Development Goals[1]

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[1] This analysis formed a component of Chapter 6 of the IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security and greenhouse gas fluxes in terrestrial ecosystems

Abstract

Interlocked challenges of climate change, biodiversity loss and land degradation require transformative interventions in the land management and food production sectors to reduce carbon emissions, strengthen adaptive capacity, and maintain or increase food production to 2050. However, deciding which interventions to pursue and understanding their relative synergies with and trade-offs against social and environmental goals has been difficult without benefit of direct comparisons across a range of possible actions. This study examined a series of 40 different mitigation and adaptation options implemented through land management, value chain or risk management measures for their relative impacts across 18 Nature's Contributions to People (also known as ecosystem services) and 17 Sustainable Development Goals. We find that a relatively small number of interventions show significant positive synergies with both SDGs and NCPs, including increasing soil organic matter, improved cropland, grazing land and livestock production, sustainable sourcing, reducing postharvest waste and losses, and disaster risk management. Several interventions show strong negative impacts on either SDGs, NCPs or in some cases, both, including bioenergy, afforestation, and some risk sharing measures, like commercial crop insurance. Our results demonstrate that better understanding of benefits and trade-offs of comparative policy approaches can help decisionmakers choose the most effective, or at the very minimum, the less negative interventions for implementation in specific contexts.

1. Introduction

The world currently faces a series of interrelated problems: climate change, biodiversity and ecosystems loss, land degradation, and poverty, among others, highlighting the need for transformative solutions that cut across these challenges. This has highlighted hopes that changes in how we use land might be able to co-deliver multiple benefits, such as reduced greenhouse gas emissions, increased adaptive capacity to current and future climate changes, improved land health and quality, and improved access to and productivity of agriculture to reduce food insecurity and poverty. However, a major dilemma is how to access these multiple benefits without undue adverse side effects on other social development goals or on natural ecosystems.

Numerous potential options have been suggested to address these land challenges, and this study assesses 40 of the response options examined in the most recent IPCC report (on climate change and land) by discussing possible co-benefits and adverse side effects. These response options encompass different land use, value chain or risk management practices commonly proposed to meet diverse land challenges, ranging from mitigation to adaptation to land degradation and food security. These options were evaluated against their implications for nature, including biodiversity and water, and against their impacts on people, such as poverty reduction efforts or gender equality measures. We do so by assessing the 40 practices against 18 identified Nature's Contributions to People (NCP), a new term for ecosystem services used by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES

2019), and the 17 UN Sustainable Development Goals (SDGs), in order to identify those that result in least trade-offs and most co-benefits.

The 40 practices considered in this study were categorized into those that rely on a) land management, b) value chain management and c) risk management (Figure 1). The land management practices can be grouped according to those that are applied in agriculture, in forests, on soils, in other/all ecosystems and those that are applied specifically for carbon dioxide removal (CDR). The value chain management practices can be categorised as those based demand management and supply management. The risk management options are grouped together. Smith et al. (2019) provides further details on each of the response options and how they were evaluated.

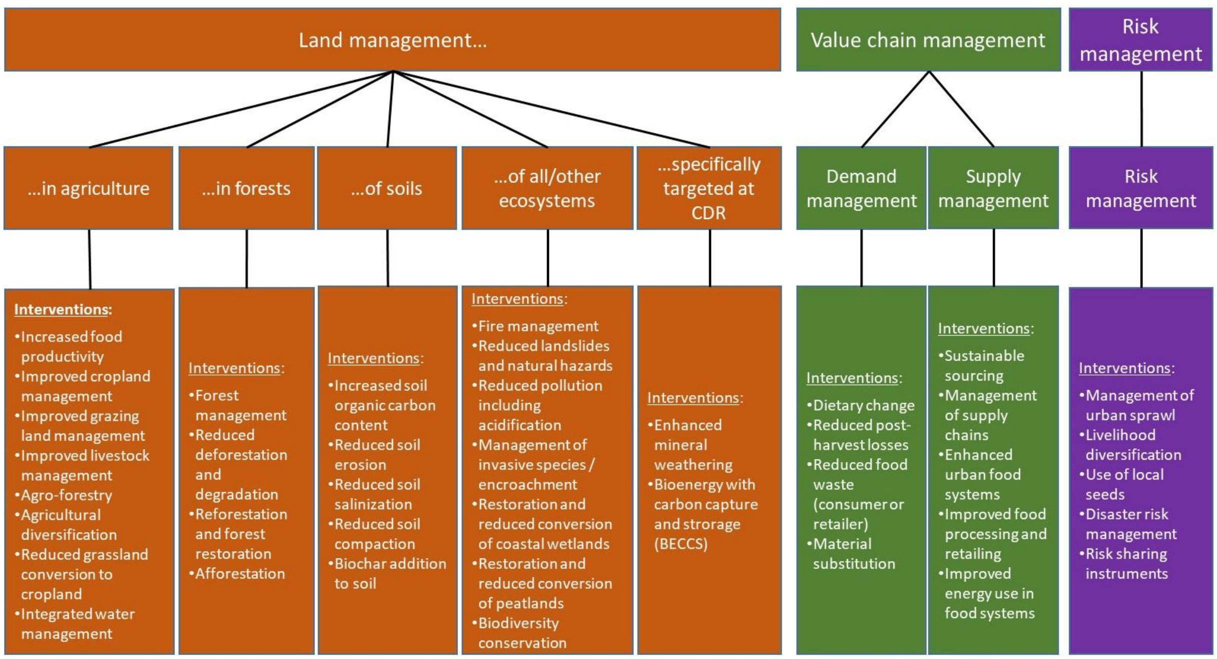

Figure 1. Broad categorisation of practices categorised into three main classes and eight sub-classes.

How the different options impact progress toward the SDG can be a useful shorthand for looking at the social impacts of policy choices, and similarly, looking at how these response options increase or decrease the supply of ecosystem services/NCP can be a useful shorthand for a more comprehensive environmental impact. Such evaluations are important as response options may lead to unexpected trade-offs (adverse side effects) or potential co-benefits with social goals and important environmental indicators like water or biodiversity. These synergies and co-benefits associated with some response options may increase their cost-effectiveness or attractiveness. Because many of these synergies are not automatic and are dependent on well-implemented and coordinated activities in appropriate environmental contexts, often requiring institutional and enabling conditions for success and participation of multiple stakeholders, it is important to identify these interactions early on in decision-making processes (IPCC 2019).

In defining co-benefits and adverse side effects, we use the IPCC AR5 WGIII definitions: co-benefits are "positive effects that a policy or measure aimed at one objective might have on other objectives, thereby increasing the total benefits for society or the environment" while adverse side-effects are "negative effects that a policy or measure aimed at one objective might have on other objectives, without yet evaluating the net effect on overall social welfare." Both co-benefits and adverse side-effects can be biophysical and/or socio-economic in nature and "are often subject to uncertainty and depend on, among others, local circumstances and implementation practices" (IPCC 2019).

Assessing policy options against their co-benefits and adverse side effects needs to account for impacts on both natural and human systems. The importance of assessing a range of climate change response options and policies against the SDGs in particular was emphasized in the IPCC 1.5 report, especially Figure SPM4 (IPCC 2018). In this approach, mitigation options were compared for their potential positive effects (synergies) or negative effects (trade-offs); negative effects from mitigation options across energy supply and demand and land were particularly noted for SDG 1 and 2 (zero poverty and no hunger) and SDG 6 and 15 (clear water and sanitation and life on land), while positive effects were noted on SDG 3 (good health) and SDG 7 (affordable and clean energy). However, as many commentators have pointed out, it is insufficient to judge progress against SDGs alone, as many of the planetary support systems that make sustainable development possible might be degraded through economic development, hence there is a need for indicators of ecosystem change and health as well beyond some of the SDGs specifically focused on ecosystems (SDG 14 and 15) (Griggs et al. 2013).

We chose to examine NCP as indicators of ecosystem benefits and services. Ecosystem services have become a useful concept to describe the benefits that humans obtain from ecosystems, while NCP is a newer approach championed by IPBES, defined as "all the contributions, both positive and negative, of living nature (i.e., diversity of organisms, ecosystems and their associated ecological and evolutionary processes) to the quality of life of people" (Díaz et al. 2018). However, IPBES has stressed NCP are a particular *way to think* of ecosystem services, rather than a replacement for the concept (Pascual et al. 2017; Díaz et al. 2018). Many mitigation actions may have positive impacts on adaptation or food production (Carpenter et al. 2009) but may also come with a decline in ecosystem provisioning, or adversely impact biodiversity (Foley et al. 2005), which is why it is important to specifically assess them. Global climate models are increasingly incorporating some ecosystem services/NCP indicators to understand vulnerability to change or loss in future climate scenarios (Schröter et al. 2005).

Table 1. List of NCPs and SDGs

NCPs (Díaz et al. 2018; IPBES 2019)	**SDGs (UN 2017)**
NCP 1: Habitat creation and maintenance	SDG 1: No poverty
NCP 2: Pollination and dispersal of seeds and other propagules	SDG 2: Zero Hunger
NCP 3: Regulation of air quality	SDG 3: Good health and well-being
NCP 4: Regulation of climate	SDG4: Quality education
NCP 5: Regulation of ocean acidification	SDG5: Gender equity
NCP 6: Regulation of freshwater quantity, flow and timing	SDG 6: Clean water and sanitation
NCP 7: Regulation of freshwater and coastal water quality	SDG7: Affordable and clean energy
NCP 8: Formation, protection and decontamination of soils and sediments	SDG 8: Decent work and economic growth
NCP 9: Regulation of hazards and extreme events	SDG9: Industry, innovation and infrastructure
NCP 10: Regulation of organisms detrimental to humans	SDG10: Reduced inequality
NCP 11: Energy	SDG 11: Sustainable cities and communities
NCP 12: Food and feed	SDG 12: Responsible production and consumption
NCP 13: Materials and assistance	SDG 13: Climate action
NCP 14: Medicinal, biochemical and genetic resources	SDG 14: Life below water
NCP 15: Learning and inspiration	SDG 15: Life on land
NCP 16: Physical and psychological experiences	SDG 16: Peace and Justice, strong institutions
NCP 17: Supporting identities	SDG 17: Partnerships to achieve the goals
NCP 18: Maintenance of options	

2. Materials and methods

Practices available to address the land challenges of climate change mitigation, climate change adaptation, desertification and land degradation and food security were collated from Chapters 2 to 5 of the IPCC Special Report on Climate Change and Land (IPCC, 2019). A thorough literature review was conducted to gather evidence on the intersections between each of these 40 practices and the 17 SDGs and 18 NCPs. Some of the categories may appear similar to each other, such as SDG 13 on "climate action" and an NCP titled "climate regulation". However, SDG 13 includes targets for both mitigation and adaptation, so options were weighed by whether they were useful for one or both. On the other hand, the NCP "regulation of climate" does not include an adaptation component, and refers 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" (Díaz et al. 2018).

For the evaluation process for NCP, we considered that NCP are about ecosystems, therefore options which may have overall positive effects, but which are *not* ecosystem-based are not included; for example, improved food transport and distribution could reduce ground-level ozone and thus improve air quality, but this is not an ecosystem-based NCP. Similarly, energy efficiency measures would increase energy availability, but the 'energy' NCP refers specifically to biomass-based fuel provisioning. This necessarily means that the land management options have more direct NCP effects than the value chain or governance options, which are less ecosystem-focused.

In evaluating NCP, we have also tried to avoid 'indirect' effects – that is a response option might increase household income which 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. These can all be considered *indirect* impacts on NCP, which were not evaluated[2]. Instead, the assessment focuses as much as possible on *direct* effects only: for example, local seeds policies preserve local landraces, which *directly* contribute to 'maintenance of genetic options' for the future. Therefore, the NCP interactions should be considered a conservative estimation of 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 NCP may trade-off with one another (Rodriguez et al 2006), so supply of one might lead to less availability of another – for example, use of ecosystems to produce bioenergy will likely lead to decreases in water availability if mono-cropped high intensity plantations are used (Gasparaos et al 2011). These interactions between NCPs are not mapped directly in our assessment.

For our assessment of SDGs, the literature was particularly uneven. Because many land management options only produce indirect or unclear effects on SDG, we did not include these where there was no literature. Therefore, the value chain and risk management options appear to offer more direct benefits for SDGs. Further, it is noted that some SDG are internally difficult to assess because they contain many targets, not all of which could be evaluated (e.g., SDG 17 is about partnerships, but has targets ranging from foreign aid to debt restructuring to technology

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

transfer to trade openness). We attempted to conduct literature searches for all key indicators per SDG (UN 2018), but found many more well represented in the literature than others. Additionally, some SDG contradict one another – for example, SDG 9 to increase industrialisation and infrastructure and SDG 15 to improve life on land; more industrialisation is likely to lead to increased resource demands with negative effects on habitats. Therefore, a positive association on one SDG measure might be directly correlated with a negative measure on another, and the table needs to be read with caution for that reason. The specific caveats on each of these interactions can be found in the supplementary material tables (SM Table 1-6).

3. Results

In the sections below, we provide the primary interactions arising from the extensive literature review and represent them visually in Tables 2-7, while textual descriptions of interactions and literature can be found in SM Tables 1-6. In all tables, colours represent the direction of impact: positive (blue) or negative (brown), and the scale of the impact (dark colours for large impact and/or strong evidence to light colours for small impact and/or less certain evidence). Supplementary tables show the values and references used to define the colour coding used in all tables. In cases where there is no evidence of an interaction or at least no literature on such interactions, the cell is left blank. In cases where there are both positive and negative interactions and the literature is uncertain about the overall impact, a note appears in the box. In all cases, many of these interactions are contextual, or the literature only refers to certain co-benefits in specific regions or ecosystems, so readers are urged to consult the supplementary tables for the specific caveats that may apply.

3.1 Interactions of the options on NCP supply

Tables 2-4 summarise the impacts of the response options on NCP supply. Examples of synergies between response options and NCP include positive impacts on habitat maintenance (NCP 1) from activities like invasive species management and agricultural diversification. For example, the latter improves resilience through enhanced diversity to mimic more natural systems and provide in-field habitat for natural pest defences (Lin 2011), while invasive species management has strong direct links to improved habitats and ecosystem diversity (Richardson & van Wilgen 2004).

Overall, several response options stand out as having co-benefits across 10 or more NCP with no notable adverse impacts on ecosystems: *improved cropland management, agroforestry, forest management and forest restoration, increased soil organic content, fire management, restoration and avoided conversion of coastal wetlands,* and *use of local seeds*.

Other response options may have strengths in some NCP but require trade-offs with others. For example, reforestation and afforestation bring many positive benefits for climate and water quality but may trade-off with food production. Several response options, including increased food productivity, bioenergy and BECCS, and some risk sharing instruments (like commercial crop insurance), have significant negative consequences across multiple NCP. While BECCS may deliver on climate mitigation, it results in a number of adverse side-effects that are significant with regard to water provisioning, food and feed availability, and loss of supporting identities if BECCS competes against local land uses of cultural importance (IPCC 2019).

Table 2. 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 sediments	Regulation of hazards and extreme events	Regulation of organisms detrimental to humans	Energy	Food and feed	Materials and assistance	Medicinal, biochemical and genetic resources	Learning and inspiration	Physical and psychological experiences	Supporting identities	Maintenance of options
Increased food productivity																		
Improved cropland management																		
Improved grazing land management																		
Improved livestock management																		
Agroforestry																		
Agricultural diversification																		
Avoidance of conversion of grassland to cropland																		
Integrated water management													+ or -					
Improved forest management and forest restoration									+ or -				+ or -					

Reduced deforestation and degradation																		
Reforestation									+ or -									
Afforestation								+ or -	+ or -									

Increased soil organic carbon content																		
Reduced soil erosion																		
Reduced soil salinisation																		
Reduced soil compaction																		
Biochar addition to soil																		

Fire management																		
Reduced landslides and natural hazards																		
Reduced pollution including acidification																		
Management of invasive species / encroachment																		
Restoration and avoided conversion of coastal wetlands												+ or -						
Restoration and avoided conversion of peatlands																		
Biodiversity conservation												+ or -						

Enhanced weathering of minerals																		

Bioenergy and BECCS[3]																				

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

Table 3. 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	Regulation of hazards and extreme events	Regulation of organisms detrimental to humans	Energy	Food and feed	Materials and assistance	Medicinal, biochemical and genetic resources	Learning and inspiration	Physical and psychological experiences	Supporting identities	Maintenance of options
Dietary change																		
Reduced post-harvest losses																		
Reduced food waste (consumer or retailer)																		
Material substitution																		

[3] FOOTNOTE: Note that this refers to large areas of bioenergy crops capable of producing large mitigation benefits (> 3 GtCO2 yr^{-1}). The effect of bioenergy and BECCS on NCPs is scale and context dependent, and smaller scale and more sustainable bioenergy would lessen these negative impacts (IPCC 2019).

Sustainable sourcing																		
Management of supply chains																		
Enhanced urban food systems																		
Improved food processing and retail																		
Improved energy use in food systems																		

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

Table 4. 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 sediments	Regulation of hazards and extreme events	Regulation of organisms detrimental to humans	Energy	Food and feed	Materials and assistance	Medicinal, biochemical and genetic resources	Learning and inspiration	Physical and psychological experiences	Supporting identities	Maintenance of options
Management of urban sprawl																		
Livelihood diversification																		
Use of local seeds																		
Disaster risk management																		
Risk sharing instruments																		

LEGEND:

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

3.2 Interactions of the options with Sustainable Development Goals

Tables 5-7 summarise the impact of the integrated response options on the UN SDGs. Some of the synergies between response options and SDGs in the literature include positive poverty reduction impacts (SDG 1) from activities like improved water management or improved management of supply chains, or positive gender impacts (SDG 5) from livelihood diversification or use of local seeds. For example, women play important roles in preserving and using local seeds, which can empower them to take more active roles in agricultural production (Ngcoya and Kumarakulasingam 2017; Bezner Kerr 2013).

Overall, several response options have co-benefits across 10 or more SDG with no adverse side effects on any SDG: *increased food production, improved grazing land management, agroforestry, integrated water management, reduced post-harvest losses, sustainable sourcing, livelihood diversification* and *disaster risk management.*

Other response options may have strengths in some SDG but require trade-offs with others. For example, use of local seeds bring many positive benefits for poverty and hunger reduction, but may reduce international trade (SDG 17). Other response options like enhanced urban food systems, management of urban sprawl, or management of supply chains are generally positive for many SDG but may trade-off with one, like clean water (SDG 6) or decent work (SDG 8), as they may increase water use or slow economic growth. Several response options, including avoidance of grassland conversion, reduced deforestation and degradation, reforestation and afforestation, biochar, restoration and avoided conversion of peatlands and coastlands, have trade-offs across multiple SDG, primarily as they prioritise land health over food production and poverty reduction. Several response options, such as bioenergy and BECCS and some risk sharing instruments, such as crop insurance, trade-off over multiple SDG with potentially significant adverse consequences.

Table 5. Impacts on the UN SDG 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 Production	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 food productivity																	
Improved cropland management																	
Improved grazing land management																	
Improved livestock management																	
Agroforestry																	
Agricultural diversification										+ or -							
Avoidance of conversion of grassland to cropland																	
Integrated water management																	
Improved forest management and forest restoration																	

Reduced deforestation and degradation	+ or -																
Reforestation	+ or -																
Afforestation																	

Increased soil organic carbon content																	
Reduced soil erosion																	
Reduced soil salinisation																	
Reduced soil compaction																	
Biochar addition to soil																	

Fire management																	
Reduced landslides and natural hazards																	
Reduced pollution including acidification																	
Management of invasive species / encroachment																	
Restoration and avoided conversion of coastal wetlands	+ or -	+ or -															
Restoration and avoided conversion of peatlands																	
Biodiversity conservation	+ or -	+ or -															

Enhanced weathering of minerals																	

Bioenergy and BECCS[4]	+ or -		+ or -														

LEGEND:

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

Table 6. Impacts on the UN SDG 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 Production	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)																	
Material substitution																	
Sustainable sourcing																	

[4] FOOTNOTE: Note that this refers to large areas of bioenergy crops capable of producing large mitigation benefits (> 3 GtCO2 yr^{-1}). The effect of bioenergy and BECCS on NCPs is scale and context dependent, and smaller scale and more sustainable bioenergy would lessen these negative impacts (IPCC 2019).

Management of supply chains																	
Enhanced urban food systems																	
Improved food processing & retail																	
Improved energy use in food systems																	

LEGEND:	Large positive impacts, strong evidence	Medium positive impacts, some evidence	Small positive impacts, low evidence	Small negative impacts, low evidence	Medium negative impacts, medium evidence	Large negative impacts, high evidence

Table 7. Impacts on the UN SDG 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 Production	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
Management of urban sprawl																	
Livelihood diversification																	
Use of local seeds		+ or -															
Disaster risk management																	
Risk sharing instruments												+ or -					

LEGEND:	Large positive impacts, strong evidence	Medium positive impacts, some evidence	Small positive impacts, low evidence	Small negative impacts, low evidence	Medium negative impacts, medium evidence	Large negative impacts, high evidence

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3.3 Interactions between SDGs and NCPS

Overall, across both categories of both SDGs and NCPs, 16 of 40 options that were evaluated deliver at least some co-benefits and have no significant adverse side-effects for the full range of NCPs and SDGs (Table 8, blue shading). This include many agriculture- and soil-based land management options, some ecosystem-based land management options, reduced post-harvest losses, sustainable sourcing, improved energy use in food systems, livelihood diversification and disaster risk management. Only three options (afforestation, bioenergy and BECCS and some types of risk sharing instruments, such as crop insurance) have potentially adverse side-effects for five or more NCP or five or more SDGs (Table 8, brown shading).

Table 8. Sums of co-benefits and adverse side-effects

	Positive Co-benefits for NCPs	Positive Co-benefits for SDGs	Adverse Side Effects for NCPs	Adverse Side Effects for SDGs
Increased food productivity	2	12	4	
Improved cropland management	10	9		
Improved grazing land management	9	10		
Improved livestock management	7	8		
Agroforestry	13	10		
Agricultural diversification	8	~7		~1
Avoidance of conversion of grassland to cropland	9	3	1	3
Integrated water management	~6	14	~1	
Improved forest management and forest restoration	~17	16	~2	
Reduced deforestation and degradation	15	8	1	~4
Reforestation	~15	~6	~2	~2
Afforestation	~11	4	~3	3
Increased soil organic carbon content	10	9		
Reduced soil erosion	7	7		
Reduced soil salinisation	4	5		
Reduced soil compaction	6	4		
Biochar addition to soil	5	3		3
Fire management	11	5		
Reduced landslides and natural hazards	6	4		
Reduced pollution including acidification	5	7		

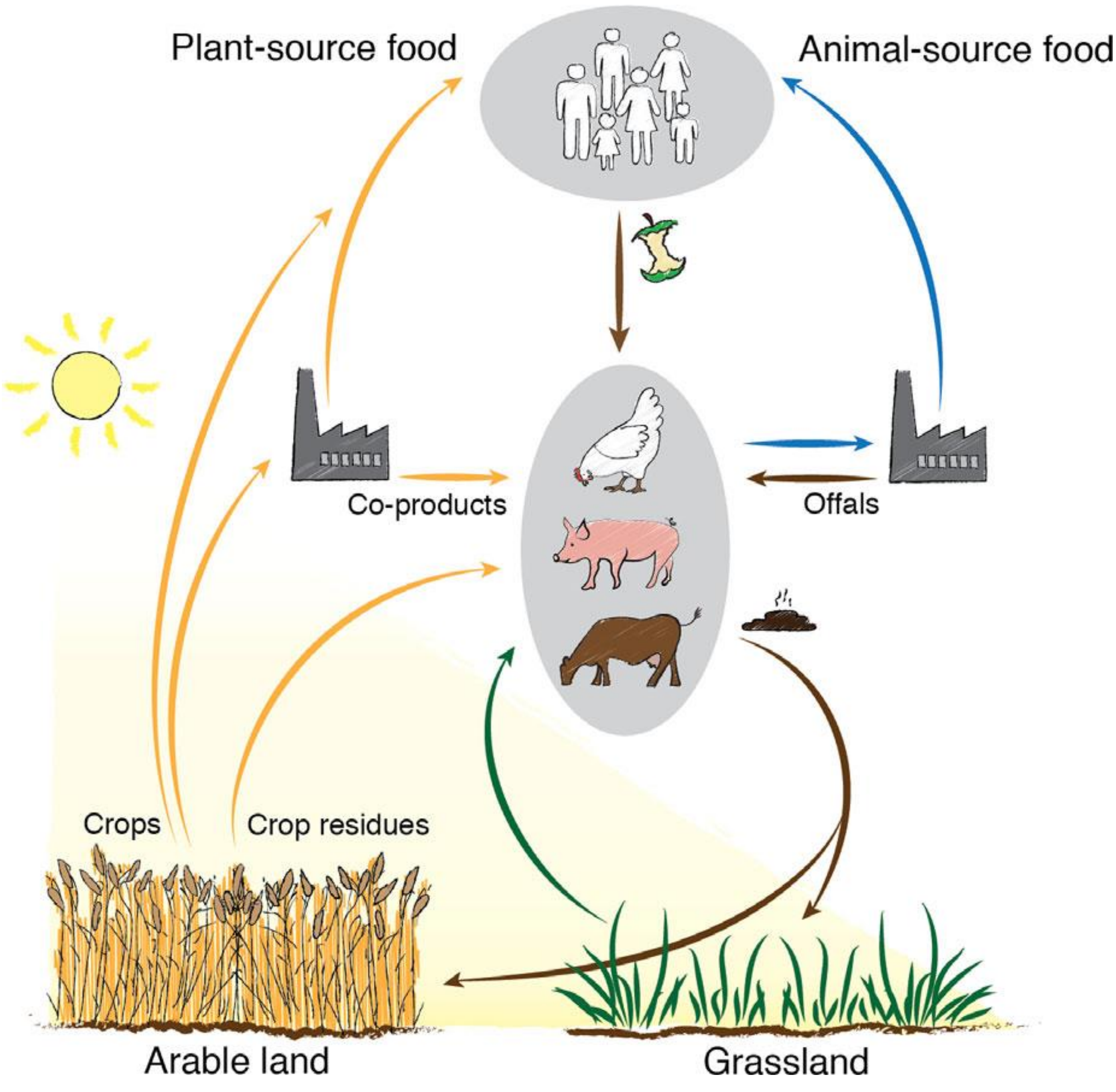
Management of invasive species / encroachment	8	6	1	
Restoration and avoided conversion of coastal wetlands	~16	~6	~1	~3
Restoration and avoided conversion of peatlands	10	3	2	4
Biodiversity conservation	~9	~9	~1	~2
Enhanced weathering of minerals	4	2	1	
Bioenergy and BECCS	4	6	12	~5
Dietary change	4	9		2
Reduced post-harvest losses	5	12		
Reduced food waste (consumer or retailer)	5	11		2
Material substitution	2	5	1	2
Sustainable sourcing	8	12		
Management of supply chains	2	14		1
Enhanced urban food systems	8	14		1
Improved food processing & retail		11		1
Improved energy use in food systems		7		
Management of urban sprawl	9	11		1
Livelihood diversification	2	13		
Use of local seeds	10	~12		~2
Disaster risk management	2	14		
Risk sharing instruments	1	~8	7	~5

Notes: Columns are sums of categories of co-benefits and side effects from Tables 2-7 and do not indicate magnitude of effect (e.g. large, medium or small benefits). ~ indicates a mixed effect.
Blue indicates presence of co-benefits with no adverse side effects.
Brown indicates presence of significant adverse side effects

Some interactions between NCPs and SDGs are also suggested by Table 8. Some response options stand out as being particularly good across a range of SDGs, but few NCPs: increased food productivity, dietary change, reduced food loss and waste, management of supply chains, enhanced urban food systems, improved food processing and retail, and improved energy use in food systems, livelihood diversification, disaster risk reduction and risk sharing instruments. Conversely, some options deliver co-benefits for many NCPs but few SDGs: avoidance of grassland conversion, reduced deforestation and degradation, reforestation and afforestation, restoration and avoided conversion of coastal wetlands and peatlands.

Notably, some options deliver a balanced set of co-benefits across both SDGs and NCPs: improved cropland management, improved grazing land management, improved livestock management, agroforestry, agricultural diversification, improved forest management, nearly all soil management options, reduced landslides and reduced pollution, management of invasive species, biodiversity conservation, and use of local seeds. Such interactions and synergies are noted in Figure 2.

Figure 2. Possible new figure showing interactions between NCP and SDG for a particular response option (improved cropland management??) that would look something like the below in terms of form



4. Discussion

Decisionmakers are increasingly asking for policy options that will help them meet agreed-upon global goals like the Paris Agreement or the SDGs. Our assessment across an extended literature review has been as comprehensive as possible (forty options times 18 NCPs and 17 SDGs) and robust (literature in the thousands of documents) to provide some direction to such policymaking. Below we discuss the primary findings, limitations of the study, and some future research directions.

Our findings of co-benefits and adverse side effects should be combined with attention to how the response options deliver across objectives such as mitigation, adaptation, land degradation or food security. Smith et al. (2019), which assesses the 40 options against these specific challenges, found that nine of the options deliver medium to large benefits for all four land challenges: increased food productivity, improved cropland management, improved grazing land management, improved livestock management, agroforestry, improved forest management, increased soil organic carbon content, fire management and reduced post-harvest losses. For mitigation only, five options have large potential (> 3 $GtCO_2e\ yr^{-1}$) without adverse impacts on the other land challenges: increased food productivity, reduced deforestation and degradation, increased soil organic carbon content, fire management and reduced post-harvest losses. Sixteen practices have large adaptation potential (>25 million people benefit), without adverse side-effects on other land challenges: increased food productivity, improved cropland management, agroforestry, agricultural diversification, improved forest management, increased soil organic carbon content, reduced landslides and natural hazards, restoration and reduced conversion of coastal wetlands, reduced post-harvest losses, sustainable sourcing, management of supply chains, improved food processing and retailing, improved energy use in food systems, livelihood diversification, use of local seeds, and disaster risk management.

4.1 Co-benefits for people and nature

There are a range of potential synergies and co-benefits provided by the assessed response options. For example, there are positive co-benefits between response options and important SDGs including positive poverty reduction impacts from activities like increased food productivity and livelihood diversification. Table 9 indicates the strongest positive relationships between options and specific SDGs, providing a possible template for what the better response options for each SDG might be.

Table 9. Better response options for certain SDGs

SDGs	Better Response options
SDG 1: No poverty	Increased food productivity, increased soil organic carbon, livelihood diversification, disaster risk reduction
SDG 2: Zero Hunger	Increased food productivity, increased soil organic carbon, agroforestry, agricultural

	diversification, reduced soil erosion and salinisation, reduced post-harvest losses, enhanced urban food systems, management of supply chains, disaster risk management
SDG 3: Good health and well-being	Agricultural diversification, reduced pollution, reduced post-harvest losses, management of supply chains, management of urban sprawl, disaster risk reduction
SDG4: Quality education	Disaster risk reduction, livelihood diversification, risk sharing instruments
SDG5: Gender equity	Livelihood diversification, use of local seeds, disaster risk management
SDG 6: Clean water and sanitation	Integrated water management, increased soil carbon, restoration of wetlands, dietary change, reduced losses and waste, management of urban sprawl, disaster risk management
SDG7: Affordable and clean energy	Afforestation, bioenergy, reduced losses and waste,
SDG 8: Decent work and economic growth	Reduced losses and waste, enhanced urban food systems
SDG9: Industry, innovation and infrastructure	Sustainable sourcing
SDG10: Reduced inequality	Dietary change, reduced losses, management of urban sprawl
SDG 11: Sustainable cities and communities	Reduced food waste, enhanced urban food systems, management of urban sprawl, disaster risk management
SDG 12: Responsible production and consumption	Dietary change, reduced losses and waste, enhanced urban food systems, management of urban sprawl, use of local seeds
SDG 13: Climate action	Increased food productivity, integrated water management, reduced deforestation, reforestation and afforestation, increased soil carbon content, biochar, biodiversity conservation, bioenergy & BECCS, dietary change, reduced food waste, management of urban sprawl
SDG 14: Life below water	Reduced wetland conversion, biodiversity conservation, bioenergy &BECCS
SDG 15: Life on land	Increased food productivity, improved cropland, grazing and livestock management, agroforestry, avoided

	grassland conversion, integrated water management, reduced deforestation, reforestation and afforestation, increased soil carbon, reduced soil erosion, salinisation and compaction, fire management, avoided wetland and peatland conversion, biodiversity conservation, dietary change, reduced losses and waste, management of urban sprawl
SDG 16: Peace and Justice, strong institutions	Enhanced urban food systems, use of local seeds, disaster risk reduction
SDG 17: Partnerships to achieve the goals	

Examples of positive co-benefits between response options and NCPs include positive ecosystem impacts on habitat maintenance from activities like reduced land conversion (across forests, grasslands, wetlands and peatlands) fire management. Table 10 indicates the strongest positive relationships between options and specific NCPs, providing a possible template for what the better response options for each NCP might be.

Table 10. Better response options for certain NCPs

NCPs	**Better response options**
NCP 1: Habitat creation and maintenance	Increased food productivity, agroforestry, integrated water management, improved forest management, reduced deforestation, reforestation, increased soil carbon, reduced soil erosion, fire management, restoration and avoided conversion of wetlands and peatlands, biodiversity conservation
NCP 2: Pollination and dispersal of seeds and other propagules	Reduced deforestation, biodiversity conservation
NCP 3: Regulation of air quality	Reduced soil erosion, bioenergy, management of urban sprawl
NCP 4: Regulation of climate	Reduced deforestation, reforestation, increased soil carbon, restoration of wetlands and peatlands, bioenergy, dietary change, reduced waste
NCP 5: Regulation of ocean acidification	Bioenergy & BECCS
NCP 6: Regulation of freshwater quantity, flow and timing	Integrated water management, reduced deforestation, increased soil carbon, reduced soil compaction, restoration and avoided conversion of wetlands and peatlands,

NCP 7: Regulation of freshwater and coastal water quality	Integrated water management, reduced deforestation, increased soil carbon, reduced soil erosion, salinisation and compaction, reduced pollution, restoration and avoided conversion of wetlands and peatlands,
NCP 8: Formation, protection and decontamination of soils and sediments	Improved cropland and grazing land management, improved forest management, increased soil carbon, reduced soil erosion, salinisation, and compaction, biochar, reduced landslides, , restoration and avoided conversion of wetlands and peatlands, management of urban sprawl
NCP 9: Regulation of hazards and extreme events	Fire management, reduced landslides, restoration and avoided conversion of wetlands, disaster risk reduction
NCP 10: Regulation of organisms detrimental to humans	Improved cropland management, agroforestry, agricultural diversification, increased soil carbon, use of local seeds
NCP 11: Energy	Bioenergy and BECCS,
NCP 12: Food and feed	Increased food productivity, improved cropland, grazing land and livestock management, agroforestry, agricultural diversification, integrated water management, increased soil carbon, dietary change, reduced loss and waste, enhanced urban food systems, use of local seeds, risk sharing instruments
NCP 13: Materials and assistance	Increased soil carbon, material substitution, sustainable sourcing, use of local seeds
NCP 14: Medicinal, biochemical and genetic resources	Increased soil carbon, biodiversity conservation, use of local seeds
NCP 15: Learning and inspiration	Use of local seeds
NCP 16: Physical and psychological experiences	Improved forest management, Biodiversity conservation
NCP 17: Supporting identities	Biodiversity conservation, use of local seeds
NCP 18: Maintenance of options	Biodiversity conservation, use of local seeds

The strong synergies between positive co-benefits with both NCPs and SDGs on a number of response options is an important finding that indicates there are potentially win-wins that do not require the degradation of natural capital and ecosystems to achieve poverty and development objectives (Miteva 2019). However, all too often such options are not implemented in an integrated manner, and the synergies are not managed for explicitly, which can result in lost opportunities (IPCC 2019).

4.2 Study limitations

The literature assessed points to general directions of interactions, but much more information is needed to make more accurate assessments. For nearly all interactions, we could assess only positive or negative qualitative trends, without the possibility of quantification. Further, because many of the NCPs and SDGs trade-off within and between one another, simple additive assessments cannot fully capture the range of interactions and the context for any given options needs to be considered carefully.

Assessing the literature across the global scale has also meant that many important, context-specific interactions, e.g. by location, ecosystem type, administrative unit, cannot be accounted for, and that the literature may be skewed towards some regions more than others. Importantly, all land-based options are scale dependent, and the potential adverse side effects of practices such BECCS are reflective of large-scale implementation (such as greenhouse gas removals of >3 $GtCO_2e\ yr^{-1}$). Such adverse side effects could be at least partially ameliorated if applied on a smaller share of the land, or if integrated into sustainably managed landscapes (see Smith et al. 2019).

Further, many of the positive synergies are not automatic, and are dependent on well-implemented activities requiring institutional and enabling conditions for success (IPCC 2019).

4.3 Data gaps and future research

As tables 2-7 show, there are considerable knowledge gaps. Many response options have not been investigated for their impacts on SDGs or NCPs. There are many suggestive relationships that suggest further research. These include interactions of all the response options for their impacts on gender Given that we know that women make up much of the agricultural workforce in the world, the lack of information on how various farming response options impact on gender dynamics is problematic and troubling. Further, given how important land management is for the supply of NCPs, we would expect more research to be conducted on the full range of NCPs from different land management practices, but certain NCPs have greater limitations in the literature than others (e.g. little information on pollination, or harmful pests),

4.4 Conclusions

Many land challenges can be met with existing tools and technologies, such as changing the conversion of natural ecosystems to croplands or increasing the soil carbon content using basic technologies like cover crops and minimal tillage. Use of these response options can result in numerous co-benefits, and with minimal side effects on SDGs and NCPs and other societal goals. Portfolios of different response options are possible and are applicable at different scales, from farm to international, and the fact that there is such a wide range of adaptation and mitigation responses that have the potential to make positive contributions to sustainable development, ecosystem services and other societal goals is good news. Overall, our assessment concludes that a number of response options can both make a dent in mitigation, adaptation, land degradation or food security and at the same time contribute to eradicating poverty and eliminating hunger, promoting good health and wellbeing, clean water and sanitation, and other positive benefits. However, care must be taken to acknowledge and manage any potential trade-offs, as well as encourage synergies and co-benefits. Land management-based options that require land use change can particularly adversely affect efforts to eradicate poverty and eliminate hunger (Molotoks et al., 2018); such trade-offs were identified with afforestation, BECCS and some risk sharing instruments (particularly commercial crop insurance). Ensuring that policymakers can anticipate these adverse side-effects in advance, and potentially choose the most appropriate response options for their particular contexts and challenges, will require more assessments such as these, and increased attention to these interactions in the overall literature.

Acknowledgements

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[To do]

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Supplementary Online Material for "The impact of interventions in the global land and agri-food sectors on Nature's Contributions to People and the UN Sustainable Development Goals"

Table S1 Literature on 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 sediments**	**Regulation of hazards and extreme events**	**Regulation of organisms detrimental to humans**	**Energy**	**Food and feed**	**Materials and assistance**	**Medicinal, biochemical and genetic resources**	**Learning and inspiration**	**Physical and psychological experiences**	**Supporting identities**	**Maintenance of options**
	Increased food productivity	Higher productivity spares land (e.g. Balmford et al. 2018) especially if intensification is done sustainably.	Likely may reduce native pollinators if reliant on increased chemical inputs (Potts et al. 2010) but not if through sustainable intensification.	N/A	N/A	Increased food productivity might be achieved through increased pesticide or fertiliser use, which causes runoff and dead zones in oceans (Beusen et al. 2016).	Food productivity increases could impact water quality if increases in chemicals used, but evidence is mixed on sustainable intensification (Rockström et al. 2009; Mueller et al. 2012).	Food productivity increases could impact water flow due to demand for irrigation (Rockström et al. 2009; Mueller et al. 2012).	Intensification through additional input of nitrogen fertiliser can result in negative impacts on climate, soil, water and air pollution (Tilman et al. 2002).	N/A	Increasing food production through agro-chemicals may increase pest resistance over time (Tilman et al. 2002).	N/A	Sustainable intensification has potential to close yield gaps (Tilman et al. 2011).	N/A	N/A	N/A	N/A	N/A	N/A
	Improved cropland management	Improved cropland management can contribute to diverse agroecosystems (Tscharntke et al. 2005) and promotes soil biodiversity (Oehl et al. 2017)	Better crop management can contribute to maintaining native pollinators (Gardiner et al. 2009).	N/A	See main text for mitigation potentials	Mitigation potential (see main text) will reduce ocean acidification.	Cropland conversion has major impacts on water quantity (Scanlon et al. 2007). Cropland management practices such as conservation tillage improve downstream water quality (Fawcett et al. 1994).	Cropland conversion leads to poorer water quality due to runoff (Scanlon et al. 2007).	Improved cropland management has positive impacts on soils (see main text) (Kern et al. 2003).	N/A	Some forms of improved cropland management can decrease pathogens and pests (Tscharntke et al. 2016).	N.A	Conservation agriculture contributes to food productivity and reduces food insecurity (Rosegrant and Cline 2003 ; Dar & Gowda 2011; Godfrey & Garnett 2014)	N/A	N/A	N/A	N/A	Many cropping systems have cultural components (Tenberg et al 2012).	N/A
Agriculture	**Improved grazing land management**	Can contribute to improved habitat (Pons et al. 2003; Plantureux et al 2005).	N/A	N/A	See main text for mitigation potentials	Mitigation potential (see main text) will reduce ocean acidification.	Likely will improve water quality (Hibbert 1983).	Likely will improve water flow (Hibbert 1983)..	Improved grassland management increases soil carbon and quality (Conant et al. 2001).	N/A	N/A	N/A	Improved grassland management could contribute to food security (O'Mara 2012)	Grassland management can provide other materials (e.g. biofuel materials) (Prochnow et al. 2009)	N/A	N/A	N/A	Many pastoralists have close cultural connections to livestock (Ainslie 2013)	N/A

	Improved livestock management	Can contribute to improved habitat if more efficient animals used, leading to less feed required (Strassburg et al. 2014)	N/A	N/A	See main text for mitigation potentials	Mitigation potential (see main text) will reduce ocean acidification.	N/A	Improved industrial livestock production can reduce water contamination (e.g. reduced effluents) (Hooda et al 2000). Improved livestock management can contribute to better water quality such as through manure management (Herrero & Thornton 2013)	N/A	N/A	N/A	N/A	Improved livestock management can contribute to reduced food insecurity among smallholder pastoralists (van't Hooft et al. 2012).	Livestock production also produces materials for use (leather, etc) (Hesse 2006)	N/A	N/A	N/A	Many pastoralists have close cultural connections to livestock (Ainslie 2013)	N/A
	Agro-forestry	Agroforestry mimics natural diversity and can improve habitat (Jose 2009).	Even intensive agroforestry can be beneficial for pollinators (Klein et al 2002).	Trees in the landscape can remove air pollutants (Sutton et al., 2007)	See main text for mitigation potentials	Mitigation potential (see main text) will reduce ocean acidification.	Planting trees on farms can increase soil water infiltration capacity (Ilstedt et al. 2007). Agroforestry can be used to increase ecosystem services benefits, such as water quantity and quality (Jose 2009)	N/A	Likely to improve soil (Rao et al. 1997)	Agroforestry can reduce vulnerability to hazards like wind and drought (Thorlakson & Neufeldt 2012).	Landscape diversity generally improves opportunities for biological pest control (Gardiner et al. 2009); reduces pests/pathogens on smallholder farms (Vignola et al., 2015)	Agroforestry can be used to produce biomass for energy (Mbow et al., 2014).	Agroforestry contributes to food productivity and reduces food insecurity (Mbow et al. 2014).	Produces timber, firewood and animal fodder (Mbow et al., 2014)	Can provide medicinal and other resources (Rao et al., 2004).	N/A	N/A	Many cropping systems have cultural components (Rao et al., 2014)	Can contribute to maintaining diversity through native plantings (Rao et al., 2014).
	Agricultural diversification	Crop diversification improves resilience through enhanced diversity to mimic more natural systems and provide in-field habitat for natural pest defences (Lin 2011)	Diversification can enhance pollinator diversity (Altieri & Letrouneau 1982; Sardinas & Kremen 2015)	N/A	N/A	N.A	N/A	N/A	Diversification can introduce some crops that may have positive soil qualities (eg nitrogen fixation) and crop rotation with multiple crops can improve soil carbon (McDaniel et al. 2014).	N/A	Diverse agroecosystems tend to have less detrimental impacts from pests (Gardiner et al 2009; Altieri & Letourneau 1982)	N/A	Diversification is associated with increased access to income and additional food sources for the farming household (Pretty et al. 2003; Ebert 2014)	Diversification could provide additional materials and farm benefits (Van Huylenbroeck et al. 007)	Some agricultural diversification can produce medicinal plants (Chauhan 2010).	N/A	N/A	Many cropping systems have cultural components (Rao et al., 2014)	Can contribute to maintaining diversity through native plantings (Sardiñas et al. 2015)
	Avoidance of conversion of grassland to cropland	Can preserve natural habitat (Peeters, 2009)	N/A	N/A	See main text for mitigation potentials	Mitigation potential (see main text) will reduce ocean acidification.	Will likely improve water quality (inferred from improved soil quality in Saziozzi et al., 2001)	Will likely improve water flow (inferred from improved soil quality in Saziozzi et al., 2001)	Will improve soil quality (Saziozzi et al., 2001)	N/A	Diverse agroecosystems tend to have less detrimental impacts from pests (Gardiner et al 2009; Altieri & Letourneau 1982)	N/A	Reducing cropland conversion can reduce food production (West et al. 2010).	N/A	N/A	N/A	N/A	N/A	Retaining natural ecosystems can preserve genetic diversity (Ekins et al., 2003).

	Integrated water management	Ecosystem health and services can be enhanced by improving water management (Boelee E and E 2011). Securing ecosystem (Lloyd et al. 2013), integrated ecosystem-based management into water resources planning and management, linking ecosystem services and water security (Nicole Bernex 2016), improving correlation between amount of water resources and supply ecosystem services, combining water resources management and supply of ecosystem services (Liu et al. 2016).	Some integrated water management strategies generate synergies between multiple ecosystem services, such as pollination, yield and farm profitability (Hipólito et. al, 2018).	IWM practices exert strong influence on ecosystem structure and function, with potentially large implications for regulating air quality (Xia et al., 2017; Hardiman et al, 2019).	IWM supports favourable forests conditions thereby influencing the storage and flow of water in watersheds (Eisenbies et al. 2007) which are important for regulating microclimates (Pierzynski et al., 2017).	N/A	Improving regulations for water sharing, trading and pricing (ADB 2016), water smart appliance, water smart landscapes (Dawadi and Ahmad 2013), common and unconventional water sources in use (Rengasamy 2006) will increase water quantity.	Improving regulation to prevent aquifer and surface water depletion, controlling over water extraction, improvement of water management and management of landslides and natural hazards. Watering shifting sand dunes (sprinkler), water resources conservation (Nejad 2013; Pereira 2002a), enhancing rainwater management, reducing recharge and increasing water use in discharge areas (DERM 2011).	IWM provide co-benefits such as healthier soils, more resilient and productive ecosystems (Grey and Sadoff 2007; Liu et al. 2017; Scott et al. 2011)	Change in water availability through improving co-managing floods and groundwater depletion at the river basin such as Managed Aquifer Recharge (MAR), Underground Taming of Floods for Irrigation (UTFI), restore over-allocated or brackish aquifers, groundwater dependent ecosystems protection, reducing evaporation losses are significantly contributed to response climate change and reduced impacts of extreme weather event in desertification areas (Dillon and Arshad 2016b).		IWM can support the production of biomass for energy and firewood (Mbow et al., 2014).	Increasing demand for food, fiber and feed will put great strains on land, water, energy and other resources (WBCSD, 2014). Water conservation and balance in the use of natural resources enforcement (based water resources, water conservation measures, water allocations) (Ward et al. 2008) are good options to response climate change and nature's prevention.	IWM supports favourable forests conditions thereby providing wood and fodder and other materials (Locatelli et al. 2015a). However, conservation restrictions on the storage and flow of water in watersheds (Eisenbies et al. 2007) can restrict the access to resources (e.g. firewood).					

Forests	**Forest management and forest restoration**	Forest landscape restoration specifically aims to regain ecological integrity and enhance human well-being in deforested or degraded forest landscape (Maginnis and Jackson 2007; Stanturf et al. 2014). For example, facilitating tree species mixture means storing at least as much carbon as monocultures while enhancing biodiversity (Hulvey et al. 2013). Selective logging techniques are "middle way" between deforestation and total protection, allowing to retain substantial levels of biodiversity, carbon, and timber stocks (Putz et al. 2012),	Likely contributes to native pollinators (Kremen et al. 2007)	Trees remove air pollution by the interception of particulate matter on plant surfaces and the absorption of gaseous pollutants through the leaf stomata. Computer simulations with local environmental data reveal that trees and forests in the conterminous United States removed 17.4 million tonnes (t) of air pollution in 2010 (range: 9.0–23.2 million t), with human health effects valued at 6.8 billion U.S. dollars (range: $1.5–13.0 billion) (Novak et al., 2014)	See main text for mitigation potentials	Mitigation potential (see main text) will reduce ocean acidification.	Forest cover can stabilise intense run-off during storms and flood events (Locatelli et al. 2015a) .Mangroves can protect coastal zones from extreme events (hurricanes) or sea level rise. However, forests also can have adverse side-effects for reduction of water yield and water availability for human consumption (Bryan and Crossman 2013).	Forests tend to maintain water quality by reducing runoff and trapping sediments and nutrients (Idris Medugu et al. 2010a; Salvati et al. 2014). Precipitation filtered through forested catchments delivers purified ground and surface water (co-benefits) (Calder 2005; Ellison et al. 2017; Neary et al. 2009).	Forests counteract wind-driven degradation of soils, and contribute to soil erosion protection and soil fertility enhancement for agricultural resilience (Locatelli et al. 2015a).	Forest cover can stabilise land against catastrophic movements associated with wave action and intense run-off during storms and flood events (Locatelli et al. 2015a). Reducing harvesting rates and prolonging rotation periods may induce an increased vulnerability of stands to external disturbances and catastrophic events (Yousefpour et al. 2018). Forest management strategies may decrease stand-level structural complexity and may make forest ecosystems more susceptive to natural disasters like wind throws, fires, and diseases (Seidl et al. 2014).	Forests can contribute to weed and pest control and landscape diversity generally improves opportunities for biological pest control (Gardiner et al. 2009)	SFM may increase availability of biomass for energy (Kraxner et al 2003; Sikkema et al 2014)	The proximity of forest to cropland constitutes a threat to livelihoods in terms of crop raiding by wild animals and in constraints in availability of land for farming (Few 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. 2016; Smith et al. 2013). An increase in global forest area can lead to increases in food prices through increasing land competition (Calvin et al. 2014; Kreidenweis et al. 2016; Reilly et al. 2012; Smith et al. 2013; Wise et al. 2009).	Forests provide wood and fodder and other materials (Locatelli et al. 2015a). However, conservation restrictions to preserve ecosystem integrity can restrict the access to resources (e.g. firewood).	Can provide medicinal and other resources.	Natural ecosystems often inspire learning (Turtle et al., 2015)	Forest landscape restoration specifically aims to enhance human well-being (Maginnis and Jackson 2007; Stanturf et al. 2014). Afforestation/reforestation and avoided deforestation benefit biodiversity and species richness, and generally improve the cultural and recreational value of ecosystems (co-benefits) (Knoke et al. 2014).	Many forest landscapes have cultural ecosystems services components (Plieninger et al. 2015)	Retaining natural ecosystems can preserve genetic diversity (Ekins et al., 2003).

	Reduced deforestation and degradation	Reduced deforestation can enhance connectivity between forest areas and conserve biodiversity hotspots (Ellison et al. 2017; Locatelli et al. 2011,a 2015a)	Likely contributes to native pollinators (Kremen et al. 2007)	Trees can improve air pollution problems (Novak et al., 2014)	See main text for mitigation potentials	Mitigation potential (see main text) will reduce ocean acidification.	Forests tend to maintain water quality by reducing runoff and trapping sediments and nutrients (Idris Medugu et al. 2010a; Salvati et al. 2014).	Due to evapotranspiration, trees recharge atmospheric moisture, contributing to rainfall locally and in distant location, and trees' microbial flora and biogenic volatile organic compounds can directly promote rainfall (Ameth et al. 2010). Trees enhance soil infiltration and, under suitable conditions, improve groundwater recharge (Calder 2005; Ellison et al. 2017; Neary et al. 2009).	Forests counteract wind-driven degradation of soils, and contribute to soil erosion protection and soil fertility enhancement for agricultural resilience (Locatelli et al. 2015a).	Forest cover can stabilise land against catastrophic movements associated with wave action and intense run-off during storms and flood events (Locatelli et al. 2015a)	Landscape diversity generally improves opportunities for biological pest control (Gardiner et al. 2009)	Reduced deforestation may increase availability of some wood for energy and industry	The proximity of forest to cropland constitutes a threat to livelihoods in terms of crop raiding by wild animals (Few 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. 2016; Smith et al. 2013) that can lead to increases in food prices (Calvin et al. 2014; Kreidenweis et al. 2016; Reilly et al. 2012; Smith et al. 2013; Wise et al. 2009).	Could increase availability of biomass (Griscom et al., 2017)	Reduced deforestation can protect forest medicinal plants (Arnold & Perez 2001)	Natural ecosystems often inspire learning (Turtle et al., 2015)	Forest ecosystems often support recreational opportunities (Liddle 1997)	Many forest landscapes have cultural ecosystems services components (Plieninger et al. 2015)	Retaining natural ecosystems can preserve genetic diversity (Ekins et al., 2003).
	Reforestation	Forest landscape restoration specifically aims to regain ecological integrity and enhance human well-being in deforested or degraded forest landscape (Maginnis and Jackson 2007; Stanturf et al. 2014). Adverse side-effects potentially associated to forests include establishment of non-native species, especially with the risks related to the spread of exotic fast growing tree	Likely contributes to native pollinators if native forest species used (Kremen et al. 2007)	Trees can improve air pollution problems (Novak et al., 2014)	See main text for mitigation potentials	Mitigation potential (see main text) will reduce ocean acidification.	Forests tend to maintain water quality by reducing runoff and trapping sediments and nutrients (Idris Medugu et al. 2010a; Salvati et al. 2014).	Particular activities associated with forest landscape restoration, such as mixed planting, assisted natural regeneration, and reducing impact of disturbances (e.g. prescribed burning) have positive implications for fresh water supply (Ciccarese et al. 2012; Suding et al. 2015).	Forests contribute to soil erosion protection and soil fertility enhancement (Locatelli et al. 2015a).	Forest cover can stabilise land against catastrophic movements associated with wave action and intense run-off during storms and flood events (Locatelli et al. 2015a) Some forest ecosystems can be susceptive to natural disasters like wind throws, fires, and diseases (Seidl et al. 2014).	N/A	Reforestation can increase availability of biomass for energy (Swisher 1994).	The proximity of forest to cropland constitutes a threat to livelihoods in terms of crop raiding by wild animals and in constraints in availability of land for farming (Few et al. 2017),. The competition for land between afforestation/reforestation and agricultural production is a potentially large adverse side-effect (Boysen et al.	Forests provide wood and fodder and other materials (Locatelli et al. 2015a). However, conservation restrictions to preserve ecosystem integrity can restrict the access to	Source of medicines (UNEP, 2016)	Natural ecosystems often inspire learning (Turtle et al., 2015)	Afforestation/reforestation can increase areas available for recreation and tourism opportunities (Knoke et al. 2014).	Many forest landscapes have cultural ecosystems services components (Plieninger et al. 2015)	

		species (Brundu and Richardson 2016; Ellison et al. 2017).											2017a,b; Kreidenweis et al. 2016; Smith et al. 2013). An increase in global forest area can lead to increases in food prices through increasing land competition (Calvin et al. 2014; Kreidenweis et al. 2016; Reilly et al. 2012; Smith et al. 2013; Wise et al. 2009).	resources (e.g. firewood).					
	Afforestation	Forest landscape restoration specifically aims to regain ecological integrity and enhance human well-being in deforested or degraded forest landscape (Maginnis and Jackson 2007; Stanturf et al. 2014). In the case of afforestation, simply changing the use of land to planted forests is not sufficient to increase abundance of indigenous species, as they depend on type of vegetation, scale of the land transition, and time required for a population to establish (Barry et al. 2014).	N/a	N/A	See main text for mitigation potentials	Mitigation potential (see main text) will reduce ocean acidification.	Depends on where reforesting and with what species (Scott et al. 2005). Trees enhance soil infiltration and, under suitable conditions, improve groundwater recharge (Calder 2005; Ellison et al. 2017; Neary et al. 2009).	Afforestation using some exotic species can upset the balance of evapotranspiration regimes, with negative impacts on water availability particularly in arid regions (Ellison et al. 2017; Locatelli et al. 2015a; Trabucco et al. 2008). Afforestation in arid and semiarid regions using species that have evapotranspiration rates exceeding the regional precipitation may aggravate the groundwater decline (Locatelli et al. 2015a; Lu et al. 2016). Changes in runoff affect water supply but can also contribute to changes in flood risks, and irrigation of forest plantations can increase water consumption	Afforestation and reforestation options are frequently used to counteract land degradation problems (Yirdaw et al. 2017). whereas when they are established on degraded lands they are instrumental to preserve natural forests (co-benefit) (Buongiorno and Zhu 2014). Afforestation runs the risk of decreasing soil nutrients, especially in intensively managed plantations; in one study, afforestation sites had lower soil P and N content (Berthrong et al 2009).	Some afforestation may make forest ecosystems more susceptive to natural disasters like wind throws, fires, and diseases (Seidl et al. 2014).	N/A	Afforestation may increase availability of biomass for energy use (Obersteiner et al 2006)	Future needs for food production are a constraint for large-scale afforestation plans (Locatelli et al. 2015a). Global food crop demand is expected by 50%–97% between 2005 and 2050 (Valin et al. 2014). Future carbon prices will facilitate deployment of afforestation projects at expenses of food availability (adverse side-effect), but more liberalised trade in agricultural commodities could buffer food price increases following afforestation in tropical regions (Kreidenweis et al. 2016).	Could increase availability of biomass (Griscom et al., 2017)	N/A	N/A	Green spaces support psychological wellbeing (Coldwell & Evans, 2018)	Afforestation/ reforestation can increase areas available for recreation and tourism opportunities (Knoke et al. 2014).	N/A

								(Sterling et al. 2013).											
Soils	**Increased soil organic carbon content**	Improving soil carbon can increase overall resilience of landscapes (Tscharntke et al. 2005)	N/A	N/A	See main text for mitigation potentials	Rivers transport dissolved organic matter to oceans (Hedges et al 1997), but unclear if improved SOM will decrease this and by how much.	Soil organic matter is known to increase water filtration and can regulate downstream flows (Keesstra et al., 2016)	Soil organic matter is known to increase water filtration and protects water quality (Lehmann & Kleber 2015)	Increasing SOM contributes to healthy soils (Lehmann & Kleber 2015)	N/A	Increased SOM decreases pathogens in soil (Lehmann & Kleber 2015)	N/A	Lal 2006 notes that "Food-grain production in developing countries can be increased by 24–39 (32+-11) million Mgy-1 through improving soil quality by increasing the SOC pool and reversing degradation processes".	In terms of raw materials, numerous products (e.g. pharmaceuticals, clay for bricks and ceramics, silicon from sand used in electronics, and other mineral	In terms of raw materials, numerous products (e.g. pharmaceuticals, clay for bricks and ceramics, silicon from sand used in electronics, and other minerals; SSSA, 2015) are provided by soils.	N/A	N/A	N/A	N/A

														s; SSSA, 2015) are provide d by soils.					
	Reduced soil erosion	Managing soil erosion decreases need for expanded cropland into habitats (Pimental et al 1995)	N/A	Particulate matter pollution, a main consequence of wind erosion, imposes severe adverse impacts on materials, structures and climate which directly affect the sustainability of urban cities (Al-Thani et al. 2018)	N/A	N//A	Managing soil erosion improves water quality (Pimental et al 1995)	Managing soil erosion improves water flow (Pimental et al 1995)	Will improve soil quality (Keesstra et al., 2016)	Reducing soil erosion reduces vulnerability to hazards like wind storms in dryland areas and landslides in mountainous areas (El-Swify 1997)	N/A	N/A	Managing erosion can lead to increased food production on croplands; however, other forms of management (revegetation, zero tillage) might reduce land available for food.	N/A	N/A	N/A/	N/A	N/A	N/A
	Reduced soil salinisation	Salinisation decreases soil microbial diversity (Nie et al. 2009)	N/A	N/A	N/A	N/A	N/A	Management of soil salinity improves water quality (Kotb et al. 2000; Zalidis et al 2002; Soane & Ouwerkerk 1995)	Will improve soil quality (Keesstra et al., 2016)	N/A	N/A	N/A	Reversing degradation contributes to food productivity and reduces food insecurity (Pimiental et al. 1995; Shiferaw & Holden 1999).	N/A	N/A	N/A/	N/A	N/A	N/A
	Reduced soil compaction	Preventing compaction can reduce need to expand croplands (Lal, 2001).	N/A	N/A	N/A	N/A	Compaction can increase water runoff (Soane & Ouwerkerk 1995). Management of soil compaction improves water quality and quantity (Soane & van Ouwerkerk 1995; Zalidis et al 2002)	Management of soil compaction improves water quality and quantity (Soane & van Ouwerkerk 1995; Zalidis et al 2002)	Will improve soil quality (Keesstra et al., 2016)	Compaction in soils increases rates of runoff and can contribute to floods (Hümann et al 2011)	N/A	N/A	Compactions reduces agricultural productivity and thus contributes to food insecurity (Nawaz et al 2013)	N/A	N/A	N/A	N/A	N/A	N/A
	Biochar addition to soil	N/A	N/A	N/A	See main text for mitigation potentials	Mitigation potential (see main text) will reduce ocean acidification.	Biochar improves soil water filtration and retention (Spokas et al 2011; Beck et al. 2011)	Biochar improves soil water filtration and retention (Spokas et al 2011; Beck et al. 2011)	Can improve soil quality (Sohi, 2012)	N/A	N/A	N/A	Contributes to increased food production (Smith 2016; Jefferry et al., 2017)	N/A	N/A	N/A	N/A	N/A	N/A

	Fire management	Proactive fire management can improve natural habitat (Burrows 2008).	Reducing fire risk can improve habitat for pollinators (Brown et al. 2017)	Fire management improves air quality particularly in the periurban interface (Bowman et al. 2005)	See main text for mitigation potentials	Mitigation potential (see main text) will reduce ocean acidification.	Fires affect water quality and flow due to erosion exposure (Townsend & Douglas 2000).	Fires affect water quality and flow due to erosion exposure (Townsend & Douglas 2000).	Fire cause damage to soils, therefore fire management can improve them (Certini 2005)	Will reduce risk of wildfires as a hazard (McCaffrey 2002)	Landscape diversity generally improves opportunities for biological pest control (Gardiner et al. 2009)	Will increase availability of biomass, as fuel removal is a key management strategy (Becker et al. 2009)	N/A	N/A	N/A	N/A	Reduced wildlife risk will increase recreation opportunities in landscapes (Venn & Calkin 2011).	N/A	Retaining natural ecosystems can preserve genetic diversity (Ekins et al., 2003).
	Reduced landslides and natural hazards	Can preserve natural habitat (Dolidon et al. 2009)	N/A	N/A	N/A	N/A	Likely will improve water quality (Dolidon et al. 2009)	Likely will improve water flow (Dolidon et al. 2009)	Will improve soil quality (Keesstra et al., 2016)	Will reduce risk of disasters (Dolidon et al. 2009; Kausky 2010)	N/A	N/A	Landslides are one of the natural disasters that have impacts on food security (de Haen & Hemrich 2007)	N/A	N/A	N/A	N/A	N/A	N/A
	Reduced pollution including acidification	Air pollution like acid rain has major impacts on habitats like lakes (Schindler et al 1989)	Pollution interferes with scents, which impact pollinators ability to detect resources (McFredrick et al 2008)	Will improve air quality with public health benefits (Nemet et al. 2010)	See main text for mitigation potentials	N/A	N/A	Pollution increases acidity of surface water, with likely ecological effects (Larssen et al 1999)	Soil acidification due to air pollution in a serious problem in many countries (Zhou et al. 2013)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Other ecosystems	**Management of invasive species / encroachment**	Improved management of IAS can lead to improved habitat and ecosystems (Richardson & van Wilgen 2004).	Invasive species can disrupt native plant-pollinator relations (Ghazoul 2006)	N/A	N.A	N/A	Many invasives can reduce water flow (Richardson & Van Wilgen 2004).	Invasive species can reduce water quality (Burnett et al. 2007; Chamier et al. 2012)	Likely to improve soil as invasive species generally have negative effects (Ehrenfeld & Scott 2001).	N/A	Many IAS are harmful pests (Charles & Dukes 2008).	N/A	IAS can compete with crops and reduce crop yields by billions of dollars annually (Pejchar & Mooney 2009)	Many invasives are important suppliers of materials (Pejchar & Mooney 2009).	N/A	N/A	N/A	N/A	Reducing invasives can increase biological diversity of native organisms (Simberloff 2005)

	Restoration and avoided conversion of coastal wetlands	Will preserve natural habitat (Griscom et al., 2017)	Will promote natural pollinators (Seddon et al., 2016)	N/A	See main text for mitigation potentials	Mitigation potential (see main text) will reduce ocean acidification.	The creation or restoration of wetlands, tidal marshes, or mangroves provide water retention and protect coastal cities from storm surge flooding and shoreline erosion during storms. Wetlands store freshwater and enhance water quality (Bobbink et al 2006)	Wetlands store freshwater and enhance water quality (Bobbink et al 2006)	Will improve soil quality (Griscom et al., 2017)	The creation or restoration of wetlands, tidal marshes, or mangroves provide water retention and protect coastal cities from storm surge flooding and shoreline erosion during storms (Haddad et al., 2015; Gittman et al. 2014; Kaplan et al. 2009).	Landscape diversity generally improves opportunities for biological pest control (Gardiner et al. 2009)	N/A	Mixed evidence: can affect agriculture/fisheries production when competition for land occurs, or could increase food production when ecosystems are restored (Crooks et al 2011)	Could increase availability of biomass (Griscom et al., 2017)	Wetlands can be sources of medicines (UNEP, 2016)	Natural ecosystems often inspire learning (Turtle et al., 2015)	Natural environments support psychological wellbeing (Coldwell & Evans, 2018)	Natural environments support psychological wellbeing (Coldwell & Evans, 2018)	Retaining natural ecosystems can preserve genetic diversity (Ekins et al., 2003).
	Restoration and avoided conversion of peatlands	Will preserve natural habitat (Griscom et al., 2017)	Could promote natural pollinators (Seddon et al., 2016)	N/A	See main text for mitigation potentials	Mitigation potential (see main text) will reduce ocean acidification.	Peatland restoration will improve water quality as they play important roles in water retention and drainage (Johnston 1991).	Peatland restoration will improve water quality as they play important roles in water retention and drainage (Johnston 1991).	Will improve soil quality (Griscom et al., 2017)	N/A	Landscape diversity generally improves opportunities for biological pest control (Gardiner et al. 2009)	Will reduce supply of any biomass or energy sourced from peatlands (Pin Koh 2007)	May reduce land available for smallholders in tropical peatlands (Jewitt et al 2014)	Will reduce supply of some materials sourced from peatlands (e.g palm oil, timber) (Murdiyarso et al. 2010)	Natural ecosystems are often source of medicines (UNEP, 2016)	Natural ecosystems often inspire learning (Turtle et al., 2015)	Natural environments support psychological wellbeing (Coldwell & Evans, 2018)	Natural environments support psychological wellbeing (Coldwell & Evans, 2018)	Retaining natural ecosystems can preserve genetic diversity (Ekins et al., 2003).

	Biodiversity conservation	Biodiversity conservation includes measures aiming to promote species richness and natural habitats, and to mantain them through protected areas (Cromsigt et al., 2018).	Reduced or absent populations of seed-dispersing animals result in poor to no dispersal,especially of large-seeded trees that depend on large animals such as elephants (Anzures-Dadda et al.2011; Brodie and Aslan2012; Beaune et al.2013; Brockerhoff et al. 2017). Animal pollination, which is fundamental to the reproduction and persistence of most flowering plants, is an important ecosystem service (Millennium Ecosystem Assessment 2005). As biodiversity contributes to various ecosystem processes, functions and services, the declining diversity and abundance of pollinators (mainly insects and birds) has raised concerns about the effects on both wild and crop plants (Potts et al. 2010).	Trees in the landscape ensured by protected areas can remove air pollutants (Sutton et al., 2007)	See main text for mitigation potentials		Many actions taken to increase biodiversity (eg protected areas) can also have incidental effects of improving water quantity (Egoh et al. 2009)	Many actions taken to increase biodiversity (eg protected areas) can also have incidental effects of improving water quality (Egoh et al. 2009)	Management of wild animals and protected habitats can influence soil conditions via changes in fire frequency (as grazers lower grass and vegetation densities as potential fuels) and nutrient cycling and transport (by adding nutrients to soils). Conserving and restoring megafauna in northern regions also prevents thawing of permafrost. Management of wild animals can influence land degradation processes by grazing, trampling and compacting soil surfaces, thereby altering surface temperatures and chemical reactions affecting sediment and carbon retention. (Cromsigt et al., 2018; Schmitz et al., 2018)	Management of wild animals can influence fire frequency as grazers lower grass and vegetation densities as potential fuels (Schmitz et al 2014).			Regulation of wild animals affects food for hunting and availability of potential feed for livestock (Cromsigt et al., 2018).		Source of medicines (UNEP, 2016)	Natural ecosystems often inspire learning (Turtle et al., 2015)	indigenous peoples commonly link forest landscapes and biodiversity to tribal identities, association with place, kinship ties, customs and protocols, stories, and songs (Gould et al. 2014; Lyver et al. 2017a, b).		Retaining natural ecosystems can preserve genetic diversity (Ekins et al., 2003).

	Enhanced weathering of minerals	N/A	N/A	N/A	See main text for mitigation potentials	Addition of basic minerals counteracts ocean acidification (Taylor et al., 2016)	N/A	May have negative effects on water quality (Atekwane et al. 2005)	Could improve soil quality (Rau & Caldiera 1999; Kantola et al 2017)	N/A	N/A	N/A	Can contribute to increase food production by replenishing plant available silicon, potassium and other plant nutrients (Beerling et al., 2018)	N/A	N/A	N/A	N/A	N/a	N/A
Carbon dioxide removal	**Bioenergy and BECCS**	Likely will reduce natural habitat with negative effects on biodiversity (Hof et al. 2018)	Would reduce natural pollinators due to decreased natural habitat if in competition (Keitt 2009).	The use of BECCS could reduce air pollution (SR1.5)	See main text for mitigation potentials	Mitigation potential (see main text) will reduce ocean acidification.	Will likely require water for plantations of fast growing trees and models show high risk of water scarcity if BECCS is deployed on widespread scale (Popp et al 2011; Smith et al. 2016; Hejazi et al., 2014) through both increases in water withdrawals (Hejazi et al., 2014; Bonsch et al., 2015) and changes in surface runoff (Cibin et al., 2015)	Bioenergy can affect freshwater quality via changes in nitrogen runoff from fertiliser application. However, the sign of the effect depends on what would have happened absent any bioenergy production, with some studies indicating improvements in water quality (Ng et al., 2010) and others showing declines (Sinha et al., 2019)	Will likely decrease soil quality if exotic fast growing trees used (Stoy et al. 2018)	N/A	N/A	BECCS and biofuels can contribute up to 300 EJ of primary energy by 2100 (Clarke et al., 2014).	BECCS will likely lead to significant trade-offs with food production (Smith et al 2016; Popp et al., 2017; Fujimori et al., in review)	N/A	N/A	N/A	BECCS would drive land use conversion and reduce opportunities for recreation/tourism.	BECCS would drive land use conversion and reduce culturally significant landscapes.	BECCS would drive land use conversion and reduce genetic diversity.

Table S2 Literature on Impacts on Nature’s Contributions to People of integrated response options based on value chain management

<u>Integrated response options based on value chain management</u>		**Habitat creation and maintenance**	**Pollination and dispersal of seeds and other propagules**	**Regulation of air quality**	**Regulation of climate**	**Regulation of ocean acidification**	**Regulation of freshwater quantity, flow and timing**	**Regulation of freshwater and coastal water quality**	**Formation, protection and decontamination of soils and sediments**	**Regulation of hazards and extreme events**	**Regulation of organisms detrimental to humans**	**Energy**	**Food and feed**	**Materials and assistance**	**Medicinal, biochemical and genetic resources**	**Learning and inspiration**	**Physical and psychological experiences**	**Supporting identities**	**Maintenance of options**
Demand management	**Dietary change**	Will lead to reduced expansion of ag lands, which can increase natural habitat (Tilman et al. 2001)	N/A	N/A	See main text on climate mitigation impacts	N/A	Will reduce water consumption if less water-intensive food/livestock needs to be produced (Tilman et al. 2001)	Reduced meat consumption will improve water quality (Stoll-Kleeman & O'Riordan 2015)	N/A	N/A	N/A	N/A	Will help increase global food supplies (Kastner et al. 2012)	N/A	N/A	N/A	N/A	N/A	N/A

	Reduced post-harvest losses	Will lead to reduced expansion of ag lands, which can increase natural habitat (Tilman et al. 2001)	N/A	N/A	See main text on climate mitigation impacts	N/A	Will reduce water consumption if less water-intensive food/livestock needs to be produced (Tilman et al. 2001)	N/A	N/A	N/A	Reducing postharvest losses will include measures to deal with pests, some of which could be biological (Wilson & Pusey 1985)	N/A	Will help increase global food supplies (Kastner et al. 2012)	N/A	N/A	N/A	N/A	N/A	N/A
	Reduced food waste (consumer or retailer)	Improved storage and distribution reduces food waste and the need for compensatory intensification of agricultural areas thereby creating co-benefits for reduced land degradation (Stathers et al. 2013).			See main text on climate mitigation impacts		Will reduce water consumption if less water-intensive food/livestock needs to be produced (Tilman et al. 2001)	Reduced food production will reduce N fertiliser use, improving water quality (Kibler et al. 2018)	N/A	N/A	N/A	N/A	Will help increase global food supplies (Kastner et al. 2012)	N/A	N/A	N/A	N/A	N/A	N/A
	Material substitution	Material substitution increases demand for wood, which can lead to loss of habitat (Sathre & Gustavsson 2006).			See main text on climate mitigation impacts	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Material substitution supplies building materials to replace concrete and other nonrewewables (Gustavsson & Sathre 2011)	N/A	N/A	N/A	N/A	N/A
	Sustainable sourcing	Forest certification and other sustainable sourcing schemes can reduce habitat fragmentation as compared to conventional supply chains (Brown et al. 2001; Rueda et al. 2015))	N/A	Forest certification improved air quality in Indonesia by 5% due to reduced incidence of fire (Miteva et al. 2015)	N/A	N/A	Forest certification has led to improved water flow due to decreased road construction for logging (Miteva et al. 2015)	Forest certificaiton has improved riparian waterways and reduced chemical inputs in some schemes (Rueda et al 2015)	N/A	N/A	N/A	Sustainable sourcing can supply energy like biomass (Sikkema et al. 2014)	Sustainable sourcing can supply food and other goods (G. Smith 2007)	Sustainable sourcing is increasingly important in timber imports (Irland 2008)	Sustainable sourcing can supply medicinals (Pierce & Laird 2003).	N/A	N/A	N/A	N/A
Supply management	**Management of supply chains**	N/A	N/A	Better management of supply chains may reduce energy use and air pollution in transport (Zhu et al. 2018)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Improved supply chains will help increase global food supplies (Hamprecht 2005).	Improved supply chains will help increase material supplies due to efficiency gains (Burritt & Schaltegger 2014).	N/A	N/A	N/A	N/A	N/A

	Enhanced urban food systems	Urban gardening can improve habitat and biodiversity in cities (Orsini et al. 2014; Lin et al. 2015)	Urban beekeeping has been important in keeping pollinators alive (Gunnarsson & Federsel 2014)	Urban agriculture can increase vegetation cover and improve air quality in urban areas (Cameron et al. 2012; Lin et al. 2015).	See main text on climate mitigation impacts	N/A	Water access often a constraint on urban agriculture and can increase demands (De Bon et al 2010; Badami & Ramankutty 2015).	Urban agriculture can exacerbate urban water pollution problems (pesticide runoff, etc) (Pothukuchi & Kaufmann 1999)	N/A	N/A	N/A	N/A	Local urban food production is often more accessible to local populations and can increase food security (Eigenbrod & Gruda 2015)	N/A	N/A	Urban agriculture can be used for teaching and learning (Travaline & Hunold 2010).	N/A	Urban agriculture can promote cultural identities (Baker 2004)	Urban food can contribute to preserving local genetic diversity
	Improved food processing and retail	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Improved energy use in food systems	N/A	N/A	N/A	See main text on climate mitigation impacts	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table S3 Literature on Impacts on Nature's Contributions to People of integrated response options based on risk management

<u>Integrated response options based on risk management</u>		**Habitat creation and maintenance**	**Pollination and dispersal of seeds and other propagules**	**Regulation of air quality**	**Regulation of climate**	**Regulation of ocean acidification**	**Regulation of freshwater quantity, flow and timing**	**Regulation of freshwater and coastal water quality**	**Formation, protection and decontamination of soils and sediments**	**Regulation of hazards and extreme events**	**Regulation of organisms detrimental to humans**	**Energy**	**Food and feed**	**Materials and assistance**	**Medicinal, biochemical and genetic resources**	**Learning and inspiration**	**Physical and psychological experiences**	**Supporting identities**	**Maintenance of options**
	Management of urban sprawl	Reducing urban sprawl can help preserve natural habitat in periurban areas (Pataki et al 2011)	Reducing urban sprawl will help reduce loss of natural pollinators from habitat conversion (Cane 2005)	Urban sprawl is a major contributor to air pollution (Frumkin 2002)	See main text on climate mitigation impacts		Managing urban sprawl can increase water availability (Pataki et al 2011)	Urban sprawl is associated with higher levels of water pollution due to loss of filtering vegetation and increasing impervious surfaces (Romero & Ordenes 2004; Tu et al 2007; Pataki et al 2011)	Likely to be beneficial for soils as soil sealing is major problem in urban areas (Scalenghe & Marsan 2009)	N/A	N/A		Urban sprawl often competes with land for food production and can reduce overall yields (Chen 2007, Barbero-Sierra et al., 2013)	N/A	N/A	N/A	N/A	N/A	N/A
	Livelihood diversification	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Diversification is associated with increased access to income and additional food sources for the household (Pretty et al. 2003)	Diversification can increase access to materials (Smith et al. 2017)	N/A	N/A	N/A	N/A	N/A

	Use of local seeds	Use of commercial seeds can contribute to habitat loss (Upreti & Upreti 2002)	Use of open pollinated seeds is beneficial for pollinators and creates political will to conserve them (Helicke 2015)	N/A	N/A	N/A	Local seeds often have lower water demands, as well as less use of pesticides that can contaminate water (Adhikari 2014)	Likely to contribute to less pollution as local seeds are usually grown organically (Adhikari 2014)	Likely to contribute to better soils as local seeds are usually grown organically (Adhikari 2014)	N/A	Local seeds often need less pesticides thereby reducing pest resistance (Adhikari 2014)	N/A	Local seeds can lead to more diverse and healthy food in areas with strong food sovereignty networks (Coomes et al. 2015; Bisht et al. 2018). However local seeds often are less productive than improved varieties.		Many local seeds can have multiple functions, including medicinals (Hammer & Teklu 2008)	Passing on seed information is important cultural learning process (Coomes et al. 2015)		Seeds associated with specific cultural identities for many (Coomes et al. 2015)	Food sovereignty movements have promoted saving of genetic diversity of crops through on-farm maintenance (Isakson 2009)
	Disaster risk management	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	DRM helps people avoid extreme events and adapt to climate change (Mechler et al. 2014)	N/A	N/A	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)		N/A	N/A	N/A	N/A	N/A
	Risk sharing instruments	Commercial crop insurance often encourages habitat conversion; 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.	Crop insurance is likely to impact natural pollinators due to incentives for production (Horowitz & Lichtenberg 1993)	N/A	N/A	N/A	N/A	Likely to have negative effect as crop insurance encourages more pesticide use (Horowitz & Lichtenberg 1993).	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).	N/A	Crop insurance increasess nitrogen use and leads to treating more acreage with both herbicides and insecticides (Horowitz & Lichtenberg 1993)	N/A	Crop insurance has generally lead to (modest) expansions in cultivated land area and increased food production (Claassen et al. 2011; Goodwin et al. 2004)		Insurance encourages monocropping leading to loss of genetic diversity for future (Glauber 2004)	N/A	N/A	N/A	Insurance encourages monocropping leading to loss of genetic diversity for future (Glauber 2004)

Table S4 Literature on Impacts on the UN SDG 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 Production**	**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 food productivity	Increasing farm yields for smallholders contributes to poverty reduction (Irz et al 2001; Pretty et al 2003)	Increasing farm yields for smallholders reduces food insecurity (Irz et al 2001; Pretty et al 2003).	Increased food productivity leads to better health status (Rosegrant & Cline 2003; Dar & Gowda 2011)	N/A	Increased productivity can benefit female farmers, who make up 50% of agricultural labor in sub-Saharan Africa (Ross et al 2015)	Food productivity increases could impact water quality if increases in chemicals used, but evidence is mixed on sustainable intensification (Rockstro¨m et al 2009; Mueller et al 2012).	N/A	Increased agricultural production generally (Lal 2006) contributes to increased economic growth.	N/A	Increased agricultural production can contribute to reducing inequality among smallholders (Datt & Ravallion 1998).	Increased food production can increase urban food security (Ellis & Sumberg 1998).	N/A	See main text on climate mitigation and adaptation	Increased food productivity might be achieved through increased pesticide or fertiliser use, which causes runoff and dead zones in oceans (Beusen et al 2016)	See main text on desertification and degradation	N/A	Improved agricultural productivity generally correlates with increases in trade in agricultural goods (Fader et al. 2013)
Agriculture	**Improved cropland management**	Improved cropland management increases yields for smallholders and contributes to poverty reduction (Irz et al 2001; Pretty et al 2003; Schneider & Gugerty 2011).	Conservation agriculture contributes to food productivity and reduces food insecurity (Rosegrant & Cline 2003; Dar & Gowda 2011; Godfray & Garnett 2014).Land consolidation has played an active role in China to in increase cultivated land area,promoting agricultural production scale, improving rural production conditions and	Conservation agriculture contributes to improved health through several pathways, including reduced fertiliser/pesticide use which cause health impacts (Erisman et al 2011) as well as improved food security.	N/A	N/A	Cropland management practices such as conservation tillage improve downstream and groundwater water quality (Fawcett et al 1994, Foster 2018). Good management practices can substantially decrease P losses from existing land use, to achieve	N/A	Increased agricultural production generally (Lal 2006) contributes to increased economic growth, mainly in smallholder agriculture (Abrahan and Pingali 2017).	N/A	Increased agricultural production can contribute to reducing inequality among smallholders (Datt & Ravallion 1998, Abrahan and Pingali 2017)).	N/A	Improved conservation agriculture contributes to sustainable production goals (Hobbs et al. 2008).	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	Improved agricultural productivity generally correlates with increases in trade in agricultural goods (Fader et al. 2013)

			living environment, alle-viating ecological risk and supporting for rural development (Zhou et al. 2019).				‘good’ water quality in catchment in New Zealand, United Kingdom and United States (											
	Improved grazing land management	Increases yields for smallholders and contributes to poverty reduction (Boval & Dixon 2012)	Improved grassland management could contribute to food security (O'Mara 2012)	Improved livestock and grazing management could contribute to better health among smallholder pastoralists (van't Hooft et al. 2012) but pathways are not entirely clear.	N/A	N/A	Grassland management practices can improve downstream and groundwater water quality (Foster 2018).	N/A	Improved land management for livestock can increase economic productivity, especially in global South (Pender et al 2006)	N/A	Improved pastoral management strategies can contribute to reducing inequality but are context specific (Lesorogol 2003)	N/A	Improved grassland management contributes to sustainable production goals (O'Mara 2012).	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	Grazing land management requires collective action and therefore can increase social capital and build institutions (Mearns 1996)	N/A
	Improved livestock management	Improved livestock management (e.g. better breeding) can contribute to poverty reduction for smallholder pastoralists (van't Hooft et al. 2012)	Improved livestock management can contribute to reduced food insecurity among smallholder pastoralists (van't Hooft et al. 2012).	N/A	N/A	N/A	Improved industrial livestock production can reduce water contamination (e.g. reduced effluents) (Hooda et al 2000). Improved livestock management can contribute to better water quality such as through manure management (Herrero & Thornton 2013)	N/A	Improved livestock management can increase economic productivity and employment opportunities in global South (Mack 1990)	N/A	N/A	N/A	Sustainable livestock management contributes to sustainable production goals (de Wit et al 1995).	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	Improved livestock productivity would likely correlate with increases in trade (Herrero et al. 2009)
	Agro-forestry	Agroforestry can be usefully used for poverty reduction (Leakey& Simons 1997).	Agroforestry contributes to food productivity and reduces food insecurity (Mbow et al. 2014).	Agroforestry positively contributes to food productivity and nutritious diets (Haddad 2000)	N/A	Increased use of agroforestry can benefit female farmers as it requires low overhead, but land tenure issues must be paid	Agroforestry can be used to increase ecosystem services benefits, such as water quantity and quality	Agroforestry could increase biomass for energy (Mbow et al. 2014)	Agroforestry and other forms of employment in forest management make major contributi	N/A	Agroforestry promotion can contribute to reducing inequality among smallholders	N/A	Agroforestry contributes to sustainable production goals (Mbow et al 2014).	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	N/A

						attention to (Kiptot & Franzel 2012).	(Jose 2009)		ons to global GDP (Pimental et al 1997).		(Leßmeister et al 2018).							
	Agricultural diversification	Agricultural 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; Weinberger & Lumpkin 2007).	Diversification is associated with increased access to income and additional food sources for the farming household (Pretty et al. 2003; Ebert 2014).Diversification can also reduce the risk of crop pathogens spreading across landscapes (Lin 2011).	More diversified agriculture leads to diversified diets which have better health outcomes (Block & Webb 2001; Ebert 2014; Kadiyala et al 2014) particularly for women and children (Pretty et al. 2003)	N/A	N/A	N/A	N/A	Agricultural diversification can lead to economic growth (Rahman 2009; Pingali & Rosegrant 1995). It allows farmers to choose a strategy that both increases resilience and provides economic benefits, including functional biodiversity at multiple spatial and/or temporal scales, through practices developed via traditional and/or agroecological scientific knowledge (Lin 2011 ; Kremen et al. 2012).	N/A	Increased agricultural diversification can contribute to reducing inequality among smallholders (Makate et al 2016), although there is mixed evidence of inequality also increasing in commercialised systems (Pingali & Rosegrant 1995; Weinberger & Lumpkin 2007)	N/A	N/A		N/A	See main text on desertification and degradation	N/A	N/A
	Avoidance of conversion of grassland to cropland	May reduce land available for cropping or livestock for poorer farmers ; some grassland restoration programs in China have been detrimental	Can affect food security when competition for land occurs (O'Mara 2012)	N/A	N/A	N/A	Retaining grasslands contributes to better water retention and improved quality (Scanlon et al 2007).	N/A	Reduced cropland expansion may decrease GDP (Lewandrowski et al 1999)	N/A	N/A	N/A	N/A	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	N/A

		to poor pastoralists (Foggin 2008)																
	Integrated water management	Green water harvesting contributes to alleviate poverty in Sub-Saharan Africa (Rockström and Falkenmark 2015), Improving water irrigation (Rengasamy 2006), improving rainfed agriculture (integrating soil and water management, rainfall infiltration and water harvesting, provides a large co-benefit to delivery of food security and poverty reduction (UNCTAD 2011)	Integrated, efficient, equitable and sustainable water resource management (as water for agroecosystem) plays importance for food production and benefits to people (Lloyd et al. 2013).	Water is a finite and irreplaceable resource that is fundamental to human well-being. It is only renewable if well managed. Integrated water management is vital option for reducing the global burden of disease and improving the health, welfare and productivity of populations. Today, more than 1.7 billion people live in river basins where depletion through use exceeds natural recharge, a trend that will see two-thirds of the world's population living in water-stressed countries by 2025 (UNWater 2015)	N/A	Involving both women and men in integrated water resources initiatives can increase project effectiveness and efficiency (Green & Baden 1995)	Water resource management is intended to solve watershed problems on a sustainable basis, and these problems can be categorised into lack of water (quantity), deterioration in water quality, ecological effects, poor public participation, and low output economic value for investment in watershed-related activities (Lee et al. 2018). Integrated water management, increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity, and substantially reduce the number of people suffering from water scarcity (UNWater 2015).	N/A	Water is at the core of sustainable development and is critical for socio-economic development, healthy ecosystems and for human survival itself. Integrated water managment can play a key enabling role in strengthening the resilience of social, economic and environmental systems in the light of rapid and unpredictable changes (UN Water, 2015).	N/A	IWM can increase access of industry to water for economic growth (Rahman & Varis 2005)	Water is a limiting factor in urban growth and IWM can help improve access to urban water supplies (Bao &Fang 2012)	Poor sectoral coordination and institutional fragmentation have triggered an unsustainable use of resources and threatened the long-term sustainability of food, water, and energy security (Rassul 2016).	See main text on climate mitigation and adaptation	IWM on land is likely to improve water quality runoff into oceans (Agboola & Braimoh 2009)	See main text on desertification and degradation	Integrated water management, increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity, and substantially reduce the number of people suffering from water scarcity (UN Water, 2015).	

Forestry	**Forest management and forest restoration**	May contribute to poverty reduction if conditions are right (Blomley & Ramadhani 2006; Donovan et al 2006), but conflicting data, as it may also favor large landowners who are less poor (Rametsteiner and Simula 2003).	Forest expansion can affect crop production when competition for land occurs (Angelsen 2010). An increase in global forest area can lead to increases in food prices through increasing land competition (Calvin et al. 2014b; Kreidenweis et al. 2016c; Reilly et al. 2012b; Smith et al. 2013a; Wise et al. 2009b)	N/A	N/A	Women face challenges in sustainable forest management (Mwangi et al 2011), but N/A how SFM affects gender equity.	Forests tend to maintain water quality by reducing runoff and trapping sediments and nutrients (Idris Medugu et al. 2010c; Salvati et al. 2014a). Due to evapotranspiration, trees recharge atmospheric moisture, contributing to rainfall locally and in distant location, and trees' microbial flora and biogenic volatile organic compounds can directly promote rainfall (Arneth et al. 2010). Trees enhance soil infiltration and, under suitable conditions, improve groundwater recharge (Calder 2005; Ellison et al. 2017a; Neary et al. 2009b). Particular activities associated with forest landscape restoration, such as mixed planting, assisted	SFM may increase availability of biomass for energy (Kraxner et al. 2013; Sikkema et al. 2013)	Forest management often require employment for active replanting, etc. (Ros-Tonen et al 2008)	Forestry supplies wood for industrial use (Gustavsson & Sathre 2011)	N/A	Community forest management can contribute to stronger communities (Padgee et al 2006)	Improved forest management contributes to sustainable production goals, e.g. thru certification of timber (Rametsteiner and Simula 2003).	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	Sustainable forest management often requires collective action institutions (Ros-Tonen et al 2008).	Sustainable forest management can contribute to increases in demand for wood products (e.g. certification) (McDonald & Lane 2004)

							natural regeneration, and reducing impact of disturbances (e.g. prescribed burning) have positive implications for fresh water supply (Ciccarese et al. 2012; Suding et al. 2015).											
	Reduced deforestation and degradation	May contribute to poverty reduction but conflicting data. Although poverty is a focus of many REDD+ projects (Arhin 2014), evidence is thin that poverty reduction has actually happened (Corbera et al. 2017; Porkorny et al 2013; Scheba 2018) and in some cases benefits have been captured by wealthier participants	Avoided deforestation can affect crop production when competition for land occurs (Angelsen 2010).	Reduced deforestation can enhance human well-being by microclimatic regulation for protecting people from heat stresses (Locatelli et al. 2015c) and generally improve the cultural and recreational value of ecosystems (Knoke et al. 2014).	N/A	Unclear how avoided deforestation might enhance gender equity, but REDD+ projects need to pay attention to gender issues to be successful (Westholm & Arora-Jonsson 2015)	Forests tend to maintain water quality by reducing runoff and trapping sediments and nutrients (Idris Medugu et al. 2010c; Salvati et al. 2014b). Due to evapotranspiration, trees recharge atmospheric moisture, contributing to rainfall locally and in distant location, and trees' microbial flora and biogenic volatile organic compounds can directly promote rainfall (Arneth et al. 2010). Trees enhance soil infiltration and, under suitable	Avoiding deforestation can take biofuel land out of production as they both tend to compete for land (Dixon et al. 2016)	Reduced forest exploitation may decrease GDP and thus needs to be compensated for (e.g. REDD+) (Motel et al 2009)	N/A	REDD+ has been shown to have no impact on inequality (Shresta et al 2017) or to increase inequality in some project areas (Andersson et al 2018; Pelletier et al 2018)	N/A	N/A	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	Likely to contribute to decline in trade in forest products, but increases in partnerships between donors and countries with REDD+ (Motel et al 2009).

							conditions, improve groundwater recharge (Calder 2005; Ellison et al. 2017a; Neary et al. 2009b).											
	Reforestation	May contribute to poverty reduction but conflicting data (Tschakert 2007). Many projects for reforestation may have some small impacts on poor households, while others actually increased poverty due to land losses or lack of economic impacts (Jindal et al 2008).	Forest expansion can affect crop production when competition for land occurs (Angelsen 2010). An increase in global forest area can lead to increases in food prices through increasing land competition (Calvin et al. 2014b; Kreidenweis et al. 2016c; Reilly et al. 2012b; Smith et al. 2013a; Wise et al. 2009b)	Reforestation can enhance human well-being by microclimatic regulation for protecting people from heat stresses (Locatelli et al. 2015c) and generally improve the cultural and recreational value of ecosystems (Knoke et al. 2014). Trends of forest resources of nations are found to positively correlate with UNDP Human Development Index (Kauppi et al. 2018).	N/A	N/A	Particular activities associated with forest landscape restoration, such as mixed planting, assisted natural regeneration, and reducing impact of disturbances (e.g. prescribed burning) have positive implications for fresh water supply (Ciccarese et al. 2012; Suding et al. 2015).	Reforestation can increase availability of biomass for energy (Swischer 1994).	Reforestation often require employment for active replanting, etc. (Jindal et al 2008)	N/A	N/A	N/A	N/A	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	N/A
	Afforestation	Although some have argued that afforestation can be a tool for poverty reduction (Holden et al 2003), afforestation can compete with land available for cropping and poor farmers often do not benefit from afforestation projects (McElwee 2009)	Future needs for food production are a constraint for large-scale afforestation plans (Locatelli et al. 2015c). Global food crop demand is expected by 50%–97% between 2005 and 2050 (Valin et al. 2014). Future carbon prices will facilitate deployment of afforestation projects at	Afforestation can enhance human well-being by microclimatic regulation for protecting people from heat stresses (Locatelli et al. 2015c) and generally improve the cultural and recreational value of ecosystems (Knoke et al. 2014).	N/A	N/A	Afforestation using some exotic species can upset the balance of evapotranspiration regimes, with negative impacts on water availability particularly in arid regions (Ellison et al. 2017a; Locatelli et al. 2015c;	Afforestation may increase availability of biomass for energy use (Obersteiner et al 2006)	Afforestation often requires employment for active replanting, etc. (Mather & Murray 1987).	N/A	N/A	N/A	N/A	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	N/A

			expenses of food availability (adverse side-effect), but more liberalised trade in agricultural commodities could buffer food price increases following afforestation in tropical regions (Kreidenweis et al. 2016c)	Trends of forest resources of nations are found to positively correlate with UNDP Human Development Index (Kauppi et al. 2018)			Trabucco et al. 2008). Afforestation in arid and semiarid regions using species that have evapotranspiration rates exceeding the regional precipitation may aggravate the groundwater decline (Locatelli et al. 2015a; Lu et al. 2016). Changes in runoff affect water supply but can also contribute to changes in flood risks, and irrigation of forest plantations can increase water consumption (Sterling et al. 2013)											
Soil management	**Increased soil organic carbon content**	Can increase yields for smallholders, which can contribute to poverty reduction, but because adoption often depends on exogenous factors these need to be taken into consideration (Wollni et al 2010; Kassie et al 2013).	Lal (2006b) notes that "Food-grain production in developing countries can be increased by 24–39 (32+-11) million Mgy-1 through improving soil quality by increasing the SOC pool and reversing degradation processes".	There is evidence that increasing soil organic carbon could be effective in reducing the prevalence of disease-causing helminths (Lal 2016; Wall et al. 2015). Also indirectly contributes to food	N/A	Gender impacts use of soil organic matter practices (Quansah et al 2001) but N/A how the relationship works in reverse.	Soil organic matter is known to increase water filtration and protects water quality (Lehmann & Kleber 2015)	N/A	Increased agricultural production generally (Lal 2006c) contributes to increased economic growth.	N/A	Increased agricultural production can contribute to reducing inequality among smallholders (Datt & Ravallion 1998).	N/A	Improved conservation agriculture contributes to sustainable production goals (Hobbs et al. 2008).	See main text on climate mitigation and adaptation	Rivers transport dissolved organic matter to oceans (Hedges et al 1997), but unclear if improved SOM will decrease this and by how much.	See main text on desertification and degradation	N/A	N/A

				productivity which may have impact on diets.														
	Reduced soil erosion	Can increases yields for smallholders and contributes to poverty reduction (Ananda & Herath 2003)	Contributes to agricultural productivity and reduces food insecurity (Pimentel et al. 1995; Shiferaw & Holden 1999).	Contributes to food productivity and improves farmer health (Pimentel et al. 1995; Shiferaw & Holden 1999).	N/A	N/A	Various researchers showed a relationship between impact of soil erosion and degradation on water quality indicating the source of pollutant as anthropogenic and industrial activities. in China (Issaka & Asheraf 2017). Managing soil erosion improves water quality (Pimentel et al 1995)	N/A	N/A	N/A	N/A	Particulate matter pollution, a main consequence of wind erosion, imposes severe adverse impacts on materials, structures and climate which directly affect the sustainability of urban cities (Al-Thani et al. 2018)	N/A	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	N/A
	Reduced soil salinisation	Salinisation can impoverish farmers (Duraiappah 1998) therefore preventing or reversing can increases yields for smallholders and contributes to poverty reduction.	Reversing degradation contributes to food productivity and reduces food insecurity (Pimiental et al. 1995; Shiferaw & Holden 1999).	Salinisation is known to have human health impacts: wind-borne dust and respiratory health; altered ecology of mosquito-borne diseases; and mental health consequences (Jardine et al 2007)	N/A	N/A	Management of soil salinity improves water quality and quantity (Kotb et al. 2000; Zalidis et al 2002)	N/A	N/A	N/A	N/A	N/A	N/A	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	N/A
	Reduced soil compaction	Soil compaction and other forms of degradation can impoverish farmers (Scherr 2000); prevention of	Compactions reduces agricultural productivity and thus contributes to food insecurity (Nawaz et al 2013)	Soil compaction has human health consequences as it contributes to runoff of water and pollutants into surface	N/A	N/A	Management of soil compaction improves water quality and quantity (Soane and van Ouwerkerk 1994;	N/A	N/A	N/A	N/A	N/A	N/A	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	N/A

		compaction thus contributes to poverty reduction.		and groundwaters (Soane and van Ouwerkerk 1994)			Zalidis et al 2002)											
	Biochar addition to soil	Land to produce biochar may reduce land available for smallholders, and it tends to be unaffordable for poor farmers; as of yet, few biochar projects have shown poverty reduction benefits (Leach et al 2012)	Could potentially affect crop production if competition for land occurs (Ennis et al 2012)	N/A	N/A	N/A	Biochar improves soil water filtration and retention (Spokas et al 2011)	N/A	N/A	N/A	N/A	N/A	N/A	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	N/A
	Fire management	N/A	N/A	Fire management reduces health risks from particulates (Bowman & Johnston 2005).	N/A	N/A	Fires affect water quality and flow due to erosion exposure (Townsend & Douglas 2000).	N/A	N/A	N/A	N/A	Wildfires can threaten property and human health in urban areas, with unique vulnerabilities (Gill & Stevens 2009; Winter & Fried 2010), therefore management will reduce risk to urban areas.	N/A	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	N/A
	Reduced landslides and natural hazards	Landslides can increase vulnerability to poverty (Msilimba 2010), therefore management will reduce risks to the poor	Landslides are one of the natural disasters that have impacts on food security (de Haen & Hemrich 2007)	Managing landslides reduces health risks (Haines et al 2006)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Landslide hazards are a major risk to urban areas (Smyth & Royle 2000).	N/A	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	N/A
Other ecosystem management	**Reduced pollution including acidification**	N/A	N/A	Reducing acid deposition reduces health risks, including respiratory illnesses and increased morbidity (Lübkert-Alcamo & Krzyzanowski 1995;	N/A	N/A	Pollution increases acidity of surface water, with likely ecological effects (Larssen et al 1999)	N/A	N/A	Management of pollution can increase demand for new technologies (Popp 2006).	N/A	Management of pollution can reduce exposure to health risks in urban areas (Bartone 1991)	N/A	See main text on climate mitigation and adaptation	Reduction in pollution can improve water quality running to oceans (Doney et al 2007).	See main text on desertification and degradation	N/A	N/A

				Larssen et al 1999)														
	Management of invasive species / encroachment	Invasive species removal policies have been beneficial to the poor (van Wilgen & Wannenburgh 2016)	IAS can compete with crops and reduce crop yields by billions of dollars annually (Pejchar & Mooney 2009)	IAS have strong negative effects on human well-being (Pejchar & Mooney 2009)	N/A	N/A	IAS like the golden apple snail/zebra mussel have damaged aquatic ecosystems (Pejchar & Mooney 2009)	N/A	IAS removal policies can increased employment due to need for labor (van Wilgen & Wannenburgh 2016)	N/A	N/A	N/A	N/A	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	N/A
	Restoration and avoided conversion of coastal wetlands	Impacts on poverty are mixed (Kumar et al 2011). May reduce land available for cropping, and poor design can impoverish people (Ingram et al 2006; Mangora 2011). Can also decrease vulnerability to coastal storms, however (Jones et al. 2012; Feagin et al 2010)	Mixed evidence: can affect agriculture/fisheries production when competition for land occurs, or could increase food production when ecosystems are restored (Crooks et al 2011)	Wetlands contribute to local well-being (Crooks et al 2011), and restoration generally improve the cultural and recreational value of ecosystems (Knoke et al. 2014).	N/A	N/A	Wetlands store freshwater and enhance water quality (Bobbink et al 2006)	N/A	Restoration projects often require employment for active replanting, etc. (Crooks et al. 2011).	Protecting coastal wetlands may reduce infrastructure projects in coastal areas (e.g. sea dikes, etc.) (Jones et al. 2012)	N/A	N/A	N/A	See main text on climate mitigation and adaptation	Restoration of coastal wetlands can play a large role in providing habitat for marine fish species (Bobbink et al 2006; Hale et al 2009)	See main text on desertification and degradation	N/A	N/A
	Restoration and avoided conversion of peatlands	May reduce land available for smallholders in tropical peatlands (Jewitt et al 2014)	Can affect crop production when competition for land occurs, although much use of peatlands in tropics is for palm oil, not food (Sellamuttu et al 2011)	N/A	N/A	N/A	Peatland restoration will improve water quality as they play important roles in water retention and drainage (Johnston 1991).	Peatlands in tropics are often used for biofuels and palm oil, so may reduce the availability of these (Danielsen et al 2008).	Reduced peatland exploitation may decrease GDP in Southeast Asia (Koh et al 2011)	N/A	N/A	N/A	N/A	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	N/A
	Biodiversity conservation	There is mixed evidence on the impacts of biodiversity conservation measures on poverty	Biodiversity, and its management, is crucial for improving sustainable and diversified diets (Global Panel on Agriculture and Food Systems for	Biodiversity, and its management, is crucial for improving sustainable and diversified diets (Global Panel on Agriculture	N/A	N/A	33 out of 105 of the largest urban areas worldwide rely on biodiversity conservation measures such as protected	Some biodiversity conservation measures might increase access to biomass supplies (Erb et al. 2012)							Biodiversity conservation measures like protected areas can increase ocean biodiversity (Selig et al 2014)	Indigenous peoples' roles in biodiversity conservation can increase institutions and conflict resolution (Garnett et al. 2018)	Indigenous peoples commonly link forest landscapes and biodiversity to tribal identities, association with place, kinship ties, customs and	

			Nutrition 2016). Indirectly, the loss of pollinators (due to combined causes, including the loss of habitats and flowering species) would contribute to 1.42 million additional deaths per year from non-communicable and malnutrition-related diseases, and 27.0 million lost disability-adjusted life-years (DALYs) per year (Smith et al. 2015). However, at the same time, some options to preserve biodiversity, like protected areas, may potentially conflict with food production by local communities (Molotoks et al. 2017)	and Food Systems for Nutrition 2016).			areas for some, or all, of their drinking water (Secretariat of the Convention on Biological Diversity 2008)										protocols, stories, and songs (Gould 2014; Lyver et al. 2017a, b).	
	Enhanced weathering of minerals	N/A	N/A	N/A	N/A	N/A	Mineral weathering can affect the chemical composition of soil and surface waters (Katz 1989)	N/A	N/A	Will require development of new technologies (Schuiling and Krijgsman 2006)	N/A	N/A	N/A	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	N/A
CDR	**Bioenergy and BECCS**	Bioenergy production could create jobs in agriculture, but could also compete for land with alternative	Biofuel plantations may lead to decreased food security through competition for land (Locatelli et	BECCS could have positive effects through improvements in air and water quality	No direct interaction (IPCC 2018).	No direct interaction (IPCC 2018).	Will likely require water for plantations of fast growing trees and models show high	BECCS and biofuels can contribute up to 300 EJ of primary energy by 2100 (cross-chapter box 7 on bioenergy);	Access to clean, affordable energy will help economic growth (IPCC 2018).	BECCS will require development of new technologies (Smith et al. 2016c).	No direct interaction (IPCC 2018).	No direct interaction (IPCC 2018).	Switching to bioenergy reduces depletion of natural resource	See main text on climate mitigation and adaptation	Reductions in carbon emissions will reduce ocean acidification. See main text on	See main text on desertification and degradation	No direct interaction (IPCC 2018).	No direct interaction (IPCC 2018).

		uses. Therefore, bioenergy could have positive or negative effects on poverty rates among smallholders, among other social effects (IPCC 2018).	al. 2015c). BECCS will likely lead to significant trade-offs with food production (Popp et al. 2011c; Smith et al. 2016b).	(IPCC 2018), but BECCS could have negative effects on health and wellbeing through impacts on food systems (Burns and Nicholson 2017). Additionally, there is a non-negligible risk of leakage of sequestered CO2 (IPCC 2018).			risk of water scarcity if BECCS is deployed on widespread scale (IPCC 2018).	bioenergy can provide clean, affordable energy (IPCC 2018).					s (IPCC 2018).		climate mitigation.			

Table S5 Literature on Impacts on the UN SDG of integrated response options based on value chain interventions

<u>Integrated response options based on value chain management</u>		GOAL 1: No Poverty	GOAL 2: Zero Hunger	GOAL 3: Good Health and Well-being	GOAL 4: Quality Education	GOAL 5: Gender Equality	GOAL 6: Clean Water and Sanitation	GOAL 7: Affordable and Clean Energy	GOAL 8: Decent Work and Economic Growth	GOAL 9: Industry, Innovation and Infrastructure	GOAL 10: Reduced Inequality	GOAL 11: Sustainable Cities and Communities	GOAL 12: Responsible Consumption and Production	GOAL 13: Climate Action	GOAL 14: Life Below Water	GOAL 15: Life on Land	GOAL 16: Peace and Justice Strong Institutions	GOAL 17: Partnerships to achieve the Goal
Demand management	**Dietary change**	Reduced meat consumption can free up land for other activities to reduce poverty (Röös et al. 2017; Stoll-Kleemann and O'Riordan 2015). However, reduced demand for livestock will have negative effect on pastoralists and could suppress demand for other inputs (grains) that would affect poor farmers (Garnett 2011; IPCC SR1.5)	High-meat diets in developed countries may limit improvement in food security in developing countries (Rosegrant et al. 1999); dietary change can contribute to food security goals (Godfray et al. 2010a; Bajželj et al. 2014)	Overnutrition contributes to worse health outcomes, including diabetes and obesity (Tilman and Clark 2014a; McMichael et al. 2007). Dietary change away from meat consumption has major health benefits, including reduced heart disease and mortality (Popkin 2008; Friel et al. 2008). Dietary change could contribute to 5.1 million avoided deaths per year (Springmann et al. 2016)	No direct interaction (IPCC 2018)	No direct interaction (IPCC 2018)	Reduced meat consumption will reduce water consumption. (Muller et al. 2017b) found that lower impact agriculture could be practiced if dietary change and waste reduction were implemented, leading to lower GHG emissions, lower rates of deforestation, and decreases in use of fertiliser (nitrogen and phosphorus), pesticides,	Dietary shifts away from meat to fish/fruits/vegetables increases energy use in the US by over 30% (Tom et al. 2016)	Health costs of meat-heavy diets add to health care costs and reduce GDP (Popkin 2008)	N/A	There are currently large discrepancies in diets between developed and developing nations (Sans & Combris 2015). Dietary change will reduce food inequality by reducing meat overconsumption in Western countries and free up some cereals for consumption in poorer diets (Rosegrant et al. 1999)	Dietary change is most needed in urbanised, industrialised countries and can help contribute to demand for locally grown fruits and vegetables (Tom et al. 2016)	A dietary shift away from meat can contribute to sustainable consumption by reducing greenhouse gas emissions and reducing cropland and pasture requirements (Stehfest et al. 2009; Bajželj et al. 2014).	See main text on climate mitigation and adaptation on	Dietary change away from meat might put increased pressure on fish stocks (Vranken et al. 2014; Mathijs 2015). Overall reduced emissions would decrease rate of ocean acidification (Doney et al. 2009)	See main text on desertification and degradation	N/A	N/A

							water and energy. However, Tom et al. (2016) found water footprints of fruit/veg dietary shift in the US to increase by 16%											
	Reduced post-harvest losses	Reducing food losses from storage and distribution operation can increase economic well-being without additional investment in production activities (Bradford et al. 2018; Temba et al. 2016)	Reducing food losses increases food availability, nutrition, and lower prices (Sheahan and Barrett 2017b; Abass et al. 2014; Affognon et al. 2015)	Improved storage enhances food quality and can reduce mycotoxin intake (Bradford et al. 2018; Temba et al. 2016; Stathers et al. 2013; Tirado et al. 2010) especially in humid climates (Bradford et al. 2018). The perishability and safety of fresh foods are highly susceptible to temperature increase (Bisbis et al. 2018; Ingram et al. 2016a).	Reduced losses can increase income that could be spent on education, but no data available	Postharvest losses do have a gender dimension (Kaminski and Christiaensen 2014), but unclear if reducing losses will contribute to gender equality (Rugumamu 2009)	Kummu et al. (2012a) reported that 24% of global freshwater use and 23% of global fertiliser use is attributed to food losses. Reduced post harvest losses can decrease need for additional agricultural production and irrigation.	Reduced losses would reduce energy demands in production; 2030 +- 160 trillion BTU of energy were embedded in wasted food in 2007 in the US (Cuéllar and Webber 2010)	In East and Southern Africa, postharvest loss for six major cereals was US$1.6 billion or 15% of total production value; reducing losses would thus boost GDP substantially in developing countries with PHL (Hodges et al. 2011)	Reducing PHL can involve improving infrastructure for farmers and marketers (Parfitt et al. 2010)	Poorer households tend to experience more PHL, and thus reducing PHL can contribute to reducing inequality among farmers (Hodges et al. 2011).	N/A	Reducing PHL contributes to sustainable production goals (Parfitt et al. 2010)	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	Post harvest losses contribute to higher food prices and constraints on trade (Tefera 2012)
	Reduced food waste (consumer or retailer)	Food waste tends to rise as incomes rise (Parfitt et al. 2010; Liu et al. 2013), so it is not clear what the relationship to poverty is. Could be potentially beneficial as it would free up money to spend on other activities (Dorward 2012). Redistribution of food surplus to the poor could also have impacts on poverty (Papargyropoulou et al. 2014)	People who are already food insecure tend not to waste food (Nahman et al. 2012). Reduced food waste would increase the supply of food (FAO 2011; Smith 2013), but it is unclear if this would benefit those who are food insecure in developing countries (Hertel and Baldos 2016).	Food waste can increase with healthier diets (Parizeau et al. 2015). Health and safety standards can restrict some approaches to reducing food waste (Halloran et al. 2014). Changes in packaging to reduce waste might have negative health impacts (e.g. increased contamination) (Claudio 2012)	N/A	Reducing food waste within households often falls to women (Stefan et al. 2013) and can increase their labor workload (Hebrok and Boks 2017). Women also generate more food waste and could be a site for intervention (Thyberg and Tonjes 2016)	Kummu et al. (2012a) reported that 24% of global freshwater and 23% of global fertiliser is used in the production of food losses, so reduction in food waste could provide significant co-benefits for freshwater provision and on nutrient cycling (Kummu et al. 2012). Muller et al.	Reduced losses would reduce energy demands in production; 2030 +- 160 trillion BTU of energy were embedded in wasted food in 2007 in the US (Cuéllar and Webber 2010). Food waste can be a sustainable source of biofuel (Uçkun Kiran et al. 2014)	Waste generation has grown faster than GDP in recent years (Thogerson 1996). Households in the UK throw out US$745 of food and drink each year as food waste; South Africans throw out $7billion US worth of food per year (Nahman and de Lange 2013). Reductions of postconsumer waste would	Food waste could be an important source of needed chemicals for industrial development in resource constrained countries (Lin et al. 2013)	Wealthier households tend to waste more food (Parfitt et al. 2010), but unclear how reducing waste may contribute to reducing inequality.	There have been large increases in the throughput of materials such as the food-waste stream, import and solid-waste accumulation in urban areas (Grimm et al. 2008). Reducing compostable food waste reduces need for landfills (Smit and Nasr 1992; Zaman and Lehmann 2011)	Post-consumer food waste in industrialised countries (222 million ton) is almost as high as the total net food production in sub- Saharan Africa (230 million ton). (FAO 2011), thereby reducing waste contributes to sustainable consumption.	See main text on climate mitigation and adaptation	Reducing food waste may be related to food packaging, which is a major source of ocean pollution, but relationship is not known (Hornweg et al 2013)	See main text on desertification and degradation	N/A	Food waste can contribute to higher food prices and constraints on trade (Tefera 2012)

							(2017b) found that lower impact agriculture could be practiced if dietary change and waste reduction were implemented, leading to lower GHG emissions, lower rates of deforestation, and decreases in use of fertiliser (nitrogen and phosphorus), pesticides, water and energy.		increase household income (Hodges et al. 2011)									
	Material substitution	N/A	Could increase demand for wood and compete with land for agriculture, but no evidence of this yet.	N/A	N/A	N/A	If water is used efficiently in production of wood, likely to be positive impact over cement production (Gustavsson and Sathre 2011)	Concrete frames require 60-80% more energy than wood (Börjesson and Gustavsson 2000). Material substitution can reduce embodied energy of buildings construction by up to 20% (Thormark 2006; Upton et al. 2008)	The relationship between material substitution and GDP growth is unclear (Moore et al. 1996)	Material substitution may reduce need for industrial production of cement etc. (Petersen and Solberg 2005)	N/A	Changing materials for urban construction can reduce cities' ecological footprint (Zaman and Lehmann 2013)	Material substitution is a form of sustainable production/consumption which replaces cement and other energy-intensive materials with wood (Fiksel 2006)	See main text on climate mitigation and adaptation	Overall reduced emissions would decrease rate of ocean acidification (Doney et al. 2009)	See main text on desertification and degradation	N/A	N/A
Supply management	**Sustainable sourcing**	Value adding has been promoted as a successful poverty reduction strategy in many countries (Lundy et al. 2002; Whitfield 2012; Swanson 2006). Volatility of food supply and 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. 2009), and caused welfare losses of 3% or more for poor households in many countries	Poor farmers can benefit from value-adding and new markets (Bamman 2007) and may help to improve food security by increasing its economic performance and revenues to local farmers (Reidsma et al. 2010). However, much value-adding is captured upstream, not by poor producers (McMichael	Value-chains can help increase the nutritional status of food reaching consumers (Fan et al. 2012)	Value-adding can increase income that could be spent on education, but no data available	Women are highly employed in value-added agriculture in many developing countries, but do not always gain substantive benefits (Dolan and Sorby 2003). Value-chains that target women could increase gender equity, but data is scare (Gengenbach et al. 2018)	Value-added products might require additional water use (Guan and Hubacek 2007), but depends on context.	N/A	Value-adding and export diversification generates additional employment and expands GDP in developing countries in particular (Newfarmer et al. 2009)	Value adding can create incentives to improve infrastructure in processing (Delgado 2010). Expanding value chains can incorporate new sources of food producers into industrial systems of distribution (Bloom and Hinrichs 2011)	Value-adding can be an important component of additional employment for poorer areas, and can contribute to reductions in overall inequality. However, data shows high-value agriculture is not always a pathway toward enhanced welfare (Dolan and Sorby 2003), and much value-adding is captured not by smallholders but higher up the chain (Neilson 2007)	Value-adding can increase incentives to keep peri-urban agriculture, but faces threats from rising land prices in urban areas (Midmore and Jansen 2003)	Value-adding in agriculture (.e.g. fair trade, organic) can be an important source of sustainable consumption and production (de Haen and Réquillart 2014)	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	Value-adding has a strong relationship to expanding trade in developing countries in particular (Newfarmer et al. 2009)

		(Zezza et al. 2009).	and Schneider 2011b). Food prices strongly affect food security (Lewis and Witham 2012; Regmi and Meade 2013; Fujimori et al. 2018a), and policies to decrease volatility will likely have strong impacts on food security (Timmer 2009; Torlesse et al. 2003b; Raleigh et al. 2015b).															
	Management of supply chains	Reducing food transport costs generally helps poor farmers (Altman et al. 2009). More than $200 million is generated in fresh fruit and veg trade between Kenya and the UK; much has contributed to poverty reduction and better transport could increase the amount generated (MacGregor and Vorley 2006; Muriithi and Matz 2015). Volatility of food supply and 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. 2009), and caused welfare losses of 3% or more for poor households	Improving storage efficiency can reduce food waste and health risks associated with poor storage management practices (James and James 2010a; Bradford et al. 2018; Temba et al. 2016; Stathers et al. 2013; Tirado et al. 2010). There is some limited evidence that improved transport on-farm increases food security in developing countries (Hine 1993).	Access to quality food is a major contributor to whether a diet is healthy or not (Neff et al. 2009). Increased distribution and access of packaged foods however can decrease health outcomes (Galal et al. 2010; Monteiro et al. 2011)	Reduction in staple food price costs to consumers in Bangladesh from food stability policies saved rural households $887 million total (Torlesse et al. 2003b), but N/A if this increased spending on education in households	Women and girls are often the most effected ones in households when there are food shortages (Kerr 2005; Hadley et al. 2008)	Food imports can contributed to water scarcity through "embodied" or "virtual" water accounting (Yang and Zehnder 2002; Guan and Hubacek 2007; Hanjra and Qureshi 2010; Jiang 2009)	Food supply chains and flows have adverse effects due to reliance on non-renewable energy (Kurian 2017; Scott 2017). Shifts to biofuels can destabilise food supplies (Tirado et al. 2010; Chakauya et al. 2009)	Food supply instability is often driven by price volatility, which can be driven by rapid economic growth and which can contribute to consumer price inflation and higher import costs as a percentage of GDP leading to account deficits (Gilbert and Morgan 2010)	Excessive disruptions in food supply can place strains on infrastructure (e.g. needing additional storage facilities) (Yang and Zehnder 2002). Improved food transport can create demands for improved infrastructure (Akkerman et al. 2010; Shively and Thapa 2016). For example, weatherproofing transport systems and improving the efficiency of food trade (Ingram et al. 2016a; Stathers et al. 2013) especially in countries with inadequate infrastructure and weak food distribution systems (Vermeulen et al. 2012a), can strengthen	Food volatility makes it more challenging to supply food to vulnerable regions, and likely increases inequality (Baldos and Hertel 2015; Frank et al. 2017; Porter et al. 2014; Wheeler and von Braun 2013). Improved food distribution could reduce inequality in access to high quality nutritious foods. Food insecure consumers benefit from better access and distribution (e.g. elimination of food deserts) (Ingram 2011; Coveney and O'Dwyer 2009)	Improved food distribution can contribute to better food access and stronger urban communities (Kantor 2001; Hendrickson et al. 2006). Food price spikes often hit urban consumers the hardest in food importing countries, and increasing stability can reduce risk of food riots (Cohen and Garrett 2010)	Improved storage and distribution are likely to contribute to sustainable production by impacting biomass of paper/card and aluminum and iron-ore mining used for food packaging (Ingram et al. 2016a).	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	Better transport improves chances for expanding trade in developing countries (Newfarmer et al. 2009), Well-planned trade systems may act as a buffer to supply food to vulnerable regions (Baldos and Hertel 2015; Frank et al. 2017; Porter et al. 2014; Wheeler and von Braun 2013).

										climate resilience against future climate-related shocks (Ingram et al. 2016a; Stathers et al. 2013).								
	Enhanced urban food systems	Regional food systems present opportunities for interconnectedness of the food system's component resilient food supply systems and city-regions have an important role (Brinkley et al. 2016; Rocha 2016). However, mixed evidence on if urban agriculture contributes to poverty reduction (Ellis and Sumberg 1998)	Food insecurity in urban areas is often invisible (Crush and Frayne 2011). Improved urban food systems manage flows of food into, within, and out of the cities and have large role to play in reducing urban food security (Smit 2016; Benis and Ferrão 2017a; Brinkley et al. 2016; Rocha 2016; Maxwell and Wiebe 1999), particularly in fostering regional food self-reliance (Aldababseh et al. 2018; Bustamante et al. 2014b).	Since urban poor spend a great deal of their budget on food and urban diets are exposed to more unhealthy 'fast foods' (Dixon et al. 2007), local urban food systems can contribute to enhanced nutrition in urban areas (Tao et al. 2015; Maxwell 1999; Neff et al. 2009). However, local urban agriculture also may introduce pollution into food system through toxins in soil and water (Binns et al. 2003)	School feeding programs in urban areas can increase educational attendance and outcomes (Ashe and Sonnino 2013)	Urban and Peri-urban Agriculture and Forestry (UPAF) addresses gender-based differences in accessing food since women play an important role in the provisioning of urban food (Tao et al. 2015; Binns and Lynch 1998). Women also dominate informal urban food provisioning (wet markets, street food) (Smith 1998)	Water access often a constraint on urban agriculture (de Bon et al. 2010; Badami and Ramankutty 2015). Urban agriculture can exacerbate urban water pollution problems (pesticide runoff, etc) (Pothukuchi and Kaufman 1999)	Local food production and use can reduce energy use, due to lower demand of resources for production, transport and infrastructure (Lee-Smith 2010), but depends on context (Mariola 2008; Coley et al. 2009)	Urban food systems have as one aim to stimulate local economic development and increase employment in urban agriculture and food processing (Smith 1998). As many as 50% of some cities' retail jobs are in food-related sector (Pothukuchi and Kaufman 1999)	Urban food provisioning creates demands for expanded infrastructure in processing, refrigeration, and transportation (Pothukuchi and Kaufman 1999)	Many UFS in global South (e.g. Belo Horizonte, Brazil) have goals to reduce inequality in access to food. (Dixon et al. 2007; Allen 2010)	UFS aim at improving the health status of urban dwellers, reducing their exposure to pollution levels, and stimulating economic development (Tao et al. 2015)	UFS aim to combine sustainable production and consumption with local foodsheds (Tao et al. 2015; Allen 2010)	See main text on climate mitigation and adaptation	Overall reduced emissions would decrease rate of ocean acidification (Doney et al. 2009)	See main text on desertification and degradation	Building a resilient regional food system requires adjusting to the social and cultural environment and locally-specific natural resource base and building local institutions (Akhtar et al. 2016). Production of food within cities can potentially lead to less likelihood of urban food shortages and conflicts (Cohen & Garrett 2010).	N/A
	Improved food processing and retailing	Food processing has been a useful strategy for poverty reduction in some countries (Weinberger and Lumpkin 2007; Haggblade et al. 2010)	Efficiency in food processing and supply chains can contribute to more food reaching consumers and improved nutrition (Vermeulen et al. 2012a; Keding et al. 2013)	Improved processing and distribution &storage systems can provide safer and healthier food to consumers (Vermeulen et al. 2012a) and reduce food waste and health risks associated with poor storage management	N/A	Improved food processing can displace street venders and informal food sellers, who are predominantly women (Smith 1998; Dixon et al. 2007)	Food processing and packaging activities such as washing, heating, cooling are heavily dependent on freshwater so improved postharvest storage and distribution could reduce water	Food processing and packaging activities such as heating and cooling are heavily dependent on energy so improved efficiency could reduce energy demand (Garcia and You 2016).	Phytosanitary barriers currently prevent much food export from developing countries, and improvements in processing would increase exports and GDP (Henson and Loader 2001; Jongwanich 2009).	Improvements in processing, refrigeration, and transportation will require investments in improved infrastructure (Ingram 2011)	N/A	Improved food transport can reduce cities' ecological footprints and reduce overall emissions (Du et al. 2006)	Improved food processing and agro-retailing contributes to sustainable production (Ingram 2011)	See main text on climate mitigation and adaptation	Overall reduced emissions would decrease rate of ocean acidification (Doney et al. 2009)	See main text on desertification and degradation	N/A	Improved processing increases chances for expanding trade in developing countries (Newfarmer et al. 2009)

				practices (James and James 2010a), although overpackaged prepared foods that are less healthy are also on rise (Monteiro 2009; Monteiro et al. 2011).			demand via more efficiently performing systems (Garcia and You 2016).											
	Improved energy use in food systems	Might possibly have impact on poverty by reducing farmer costs, but no data.	Utilising energy-saving strategies can support reduced food waste (Ingram et al. 2016a) and increased production efficiencies (Smith and Gregory 2013).	Organic agriculture is associated with increased energy efficiency, which have can have co-benefits by reduced exposure to agrochemicals by farm workers (Gomiero et al. 2008)	N/A	Increased efficiency might reduce women's labor workloads on farms (Rahman 2010) but data is scarce.	Increased energy efficiency (e.g. in irrigation) can lead to more efficient water use (Rothausen and Conway 2011; Ringler and Lawford 2013)	Increased energy efficiency will reduce demands for energy but can have rebound effect in expanded acreage (Swanton et al. 1996)	There is no clear association between higher energy use in agriculture and economic growth; these have become decoupled in many countries (Bonny 1993). Data is unclear though on economic impacts of potential cost savings.	N/A	N/A	N/A	Reducing energy use in agriculture contributes to sustainable production goals (Ingram et al. 2016a).	See main text on climate mitigation and adaptation	Overall reduced emissions would decrease rate of ocean acidification (Doney et al. 2009).	See main text on desertification and degradation	N/A	N/A

Table S6 Literature on Impacts on the UN SDG 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 Production**	**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**
	Management of urban sprawl	Inner city poverty closely associated with urban sprawl in US context (Frumkin 2002; Powell 1999; Jargowsky 2002; Deng and Huang 2004)	There are likely to be some benefits for food security since it is often agricultural land that is sealed by the urban expansion (Barbero-Sierra et al. 2013a). Some evidence for sprawl reducing food production, particularly in China (Chen 2007b)	Strong association between urban sprawl and poorer health outcomes (air pollution, obesity, traffic accidents) (Frumkin 2002; Lopez 2004; Freudenberg et al. 2005)	N/A	N/A	Urban sprawl is associated with higher levels of water pollution due to loss of filtering vegetation and increasing impervious surfaces (Romero and Ordenes 2004; Tu et al. 2007)	Sprawling or informal settlements often do not have access to electricity or other services, increasing chances HH rely on dirty fuels (Dhingra et al. 2008)	Sprawl is associated with rapid economic growth in some areas (Brueckner 2000). Reducing urban sprawl is part of many managed "smart growth" plans, which may reduce overall economic growth in return for sustainability benefits	Urban sprawl often increases public infrastructure costs (Brueckner 2000), and densification and redevelopment can improve equality of access to infrastructure (Jenks and Burgess 2000).	Urban sprawl is associated with inequality (Jargowsky 2002)	Urban sprawl is associated with unsustainability, including increased transport and CO_2 emissions, lack of access to services, and loss of civic life (Kombe 2005; Andersson 2006). Sustainable cities include compactness, sustainable transport, density, mixed land uses, diversity, passive solar design, and greening (Chen et al. 2008; Jabareen	Reducing urban sprawl and promoting community gardens and periurban agriculture can contribute to more sustainable production in cities (Turner 2011)	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	There are debates over the role of urban sprawl in reducing social capital and weakening participatory governance in cities (Frumkin 2002; Nguyen 2010)	N/A

									(Godschalk 2003)			2006; Andersson 2006)						
	Livelihood diversification	Diversification is associated with increased welfare and incomes and decreased levels of poverty in several country studies (Arslan et al. 2018b; Asfaw et al. 2018).	Diversification is associated with increased access to income and additional food sources for the household (Pretty 2003); likely some food security benefits but diversification can also lead to more purchased (unhealthy) foods (Niehof 2004; Barrett et al. 2001)	More diversified livelihoods have diversified diets which have better health outcomes (Block and Webb 2001; Kadiyala et al. 2014) particularly for women and children (Pretty 2003)	More diversified households tend to be more affluent, & have more disposal income for education (Ellis 1998; Estudillo and Otsuka 1999; Steward 2007), but diversification through migration may reduce educational outcomes for children (Gioli et al. 2014)	Women are participants in and benefit from livelihood diversification, such as having increased control over sources of HH income (Smith 2015), although it can increase their labor requirements (Angeles and Hill 2009)	Lack of access to affordable water may inhibit livelihood diversification (Calow et al. 2010)	Access to clean energy can provide additional opportunities for livelihood diversification (Brew-Hammond 2010; Suckall et al. 2015)	Livelihood diversification by definition contributes to employment by providing additional work opportunities (Ellis 1998; Niehof 2004)	N/A	The relationship between livelihood diversification and inequality is inconclusive (Ellis 1998). In some cases diversification reduced inequality (Adams 1994) while in others cases it increases it (Reardon et al 2000)	One part of urban livelihoods in developing countries are linkages between rural and urban areas through migration and remittances (Rakodi 1999; Rakodi & Lloyd 2002); this livelihood diversification can strengthen urban income (Ricci 2012)	Livelihood diversification does not always lead to sustainable production and consumption choices, but it can strengthen autonomy potentially leading to better choices (Elmqvist and Olsson 2007; Schneider and Niederle 2010)	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	N/A	N/A
	Use of local seeds	Many hundreds of millions of smallholders still rely on local seeds; without them they would have to find money to buy commercial seeds (Altieri et al. 2012b; McGuire and Sperling 2016; Howard 2015)	Local seeds revive and strengthen local food systems (McMichael and Schneider 2011b) and lead to more diverse and healthy food in areas with strong food sovereignty networks (Coomes et al. 2015a; Bisht et al. 2018). However local seeds often are less productive than improved varieties.	Local seed use is associated with fewer pesticides (Altieri et al. 2012b); loss of local seeds and substitution by commercial seeds is perceived by farmers to increase health risks (Mazzeo and Brenton 2013), although overall literature on links between food sovereignty and health is weak (Jones et al. 2015)	N/A	Women play important roles in preserving and using local seeds (Ngcoya and Kumarakulasingam 2017; Bezner Kerr 2013) and sovereignty movements paying more attention to gender needs (Park et al. 2015)	Local seeds often have lower water demands, as well as less use of pesticides that can contaminate water (Adhikari 2014)	N/A	Food sovereignty supporters believe protecting smallholder agriculture provides more employment than commercial agriculture (Kloppenberg 2010)	N/A	Seed sovereignty advocates believe it will contribute to reduced inequality (Wittman 2011; Park et al. 2015) but there is inconclusive empirical evidence.	Seed sovereignty can help sustainable urban gardening (Demailly and Darly 2017) which can be part of a sustainable city by providing fresh, local food (Leitgeb et al. 2016).	Locally developed seeds can both help protect local agrobiodiversity and can often be more climate resilient than generic commercial varieties, leading to more sustainable production (Coomes et al. 2015a; van Niekerk and Wynberg 2017a).	See main text on climate mitigation and adaptation	N/A	See main text on desertification and degradation	Seed sovereignty is positively associated with strong local food movements, which contribute to social capital (McMichael and Schneider 2011b; Coomes et al. 2015a; Grey and Patel 2015).	Seed sovereignty could be seen as threat to free trade and imports of genetically modified seeds (Kloppenberg 2010; Howard 2015; Kloppenburg 2014)

	Disaster risk management	DRM can help prevent impoverishment as disasters are a major factor in poverty (Basher 2006; Fothergill and Peek 2004)	Famine early warning systems have been successful to prevent impending food shortages (Genesio et al. 2011; Hillbruner and Moloney 2012)	EWS very important for public health to ensure people can get shelter and medical care during disasters (Greenough et al. 2001; Ebi and Schmier 2005)	N/A	Women often disproportionately affected by disasters; gender-sensitive EWS can reduce their vulnerability (Enarson and Meyreles 2004; Mustafa et al. 2015)	Many EWS include water monitoring components that contribute to access to clean water (Wilhite 2005; Iglesias et al. 2007). Some urban areas use water EWS successfully to monitor levels of contaminants (Hasan et al. 2009; Hou et al. 2013)	N/A	DRM can help minimise damage from disasters, which impacts economic growth (Basher 2006)	DRM can help protect infrastructures from damage during disaster (Rogers and Tsirkunov 2011)	EWS can ensure inequality is taken into account when making predictions of impacts (Khan et al. 1992)	EWS can be very effective in urban settings such as heat wave EWS and flooding EWS to minimise vulnerability (Parnell et al. 2007; Bambrick et al. 2011; Djordjević et al. 2011)	DRM can make sustainable production more possible by providing farmers with advance notice of environmental needs (Stigter et al. 2000; Parr et al. 2003)	See main text on climate mitigation and adaptation	EWS can play important role in marine management, e.g. warnings of red tide, tsunami warnings for coastal communities (Lee et al. 2005; Lauterjung et al. 2010)	See main text on desertification and degradation	DRM can reduce risk of conflict (Meier et al. 2007), increase resilience of communities (Mathbor 2007) and strengthen trust in institutions (Altieri et al. 2012b)	N/A
	Risk sharing instruments	Crop insurance reduces risks which can improve poverty outcomes by avoiding catastrophic losses, but is often not used by poorest people (Platteau et al. 2017)	Availability of crop insurance has generally lead to (modest) expansions in cultivated land area and increased food production (Claassen et al. 2011; Goodwin et al. 2004)	General forms of social protection lead to better health outcomes; unclear how much crop insurance contributes (Tirivayi et al. 2016)	Households lacking insurance may withdraw children from school after crop shocks (Jacoby and Skoufias 1997; Bandara et al. 2015)	Women farmers vulnerable to crop shocks, but tend to be more risk-averse and skeptical of commercial insurance (Akter et al. 2016; Fletschner and Kenney 2014)	Crop insurance can be indexed to weather and water access and thereby increase adapation to water stress (Hoff and Bouwer 2003). Subsidised insurance can also be linked to reductions in pesticide use to reduce non-point source pollution, which has shown success in the US and China (Luo et al. 2014)	N/A	Subsidised crop insurance contributes to economic growth in the US (Atwood et al. 1996) but at considerable cost to the governance (Glauber 2004).	N/A	N/A	N/A	Crop insurance has been implicated as a driver of unsustainable production and disincentive to diversification (Bowman and Zilberman 2013), although community risk sharing might increase diversification and production	See main text on climate mitigation and adaptation	There is mixed evidence that crop insurance may encourage excess fertiliser use (Kramer et al. 1983; Wu 1999; Smith and Goodwin 1996), which contributes to ocean pollution; however, some governments re requiring reductions in nonpoint source pollution from farms otherwise farmers lose crop insurance (Iho et al. 2015)	See main text on desertification and degradation	Community risk sharing instruments can help strenthen resilience and institutions (Agrawal 2001)	Subsidised crop insurance can be seen as a subsidy and barrier to trade (Young and Westcott 2000)