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INVITED RESEARCH REVIEW

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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

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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 increase food security. However, deciding which interventions to pursue and understanding their relative co-benefits with and trade-offs against different social and environmental goals have been difficult without comparisons across a range of possible actions. This study examined 40 different options, implemented through land management, value chains, or risk management, for their relative impacts across 18 Nature's Contributions to People (NCPs) and the 17 Sustainable Development Goals (SDGs). We find that a relatively small number of interventions show positive synergies with both SDGs and NCPs with no significant adverse trade-offs; these include improved cropland management, improved grazing land management, improved livestock management, agroforestry, integrated water management, increased soil organic carbon content, reduced soil erosion, salinization, and compaction, fire management, reduced landslides and hazards, reduced pollution, reduced post-harvest losses, improved energy use in food systems, and disaster risk management. Several interventions show potentially significant negative impacts on both SDGs and NCPs; these include bioenergy and bioenergy with carbon capture and storage, afforestation, and some risk sharing measures, like commercial crop insurance. Our results demonstrate that a better understanding of co-benefits and trade-offs of different policy approaches can help decision-makers choose the more effective, or at the very minimum, more benign interventions for implementation.

KEYWORDS
adaptation, ecosystem services, food security, land degradation, mitigation, Nature's Contribution to People, sustainable development, sustainable land management, trade-offs

1 | INTRODUCTION

The world currently faces a series of interrelated problems: climate change, loss of biodiversity and ecosystems, land degradation, food insecurity, and poverty, highlighting the need for transformative solutions that cut across these challenges (IPBES, 2018, 2019; Rockström et al., 2009; UN Environment, 2019). Changes in how land is used could tackle some of these problems and 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 (Foley et al., 2011; Kanter et al., 2018). However, a major dilemma is how to achieve these multiple benefits without undue adverse side effects on other societal goals or on natural ecosystems (Guerry et al., 2015; Meyfroidt, 2018; Mirzabaev et al., 2015).

Numerous potential options have been suggested to address these land challenges, including various practices identified within sustainable land management (SLM; Reed et al., 2015; Sanz et al., 2017). However, deciding which interventions to pursue requires understanding their relative co-benefits with and trade-offs against different social and environmental goals (Sachs et al., 2019), and has been difficult without direct comparisons across a range of possible actions (Iyer et al., 2018). While some interactions can be included in integrated assessment models (van Soest et al., 2019), others are less easily quantified, and need to be understood through different methods, such as expert assessments or literature reviews (Singh et al., 2018).

This study examines 40 of the response options identified in chapter 6 of the recent Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Change and Land (IPCC, 2019). These options encompassed different land management, value chain, or risk management practices commonly proposed to meet a diverse set of land challenges, among them mitigation, adaptation, degradation, and food security (Smith et al., 2020). These 40 options were assessed 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 evaluating the 40 practices against the 17 UN Sustainable Development Goals (SDGs), as well as 18 Nature's Contributions to People (NCPs), a new term used by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019), and 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; Table 1). NCPs and ecosystem services are related, but not precisely parallel concepts (Kadykalo et al., 2019). IPBES authors have stressed NCPs are a particular way to think of ecosystem services, rather than a replacement for the term. Rather, the concept of NCP was proposed to be a broader umbrella to engage a wider range of scholarship, particularly from the social sciences and humanities, and a larger range of values around ecosystems (Pascual et al., 2017). Both SDGs and NCPs reflect attention to the interconnected relationships between people and ecosystems. The importance of assessing a range of response options and policies against the SDGs in particular was emphasized in the IPCC Special Report on the Impacts of Global Warming of 1.5°C (Roy et al., 2018). For example, negative effects from mitigation options across energy supply and demand and land use were particularly strong for SDG 1 and 2 (zero poverty and no hunger) and SDG 6 and 15 (clean 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, 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 well beyond the SDGs specifically focused on ecosystems (e.g., SDG 14 and 15; Griggs et al., 2013). NCPs thus can be a useful proxy for both impacts on nature and benefits to humans (Ellis, Pascual, & Mertz, 2019).

Response options to land challenges may lead to unexpected adverse side effects or potential co-benefits with societal goals like SDGs and NCPs (Timko et al., 2018). In defining co-benefits and adverse side effects, we use the IPCC definitions: co-benefits are “positive effects that a policy or measure aimed at one objective might

TABLE 1 Explanation of Nature's Contributions to People (NCPs) and Sustainable Development Goals (SDGs)

SDGs	Explanation (UN, 2018)
SDG 1 No poverty	End poverty in all its forms everywhere
SDG 2 Zero hunger	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture
SDG 3 Good health and well-being	Ensure healthy lives and promote well-being for all at all ages
SDG 4 Quality education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
SDG 5 Gender equity	Achieve gender equality and empower all women and girls
SDG 6 Clean water and sanitation	Ensure availability and sustainable management of water and sanitation for all
SDG 7 Affordable and clean energy	Ensure access to affordable, reliable, sustainable, and modern energy for all
SDG 8 Decent work and economic growth	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all
SDG 9 Industry, innovation, and infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation
SDG 10 Reduced inequalities	Reduce inequality within and among countries
SDG 11 Sustainable cities and communities	Make cities and human settlements inclusive, safe, resilient, and sustainable
SDG 12 Responsible production and consumption	Ensure sustainable consumption and production patterns
SDG 13 Climate action	Take urgent action to combat climate change and its impacts
SDG 14 Life below water	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development
SDG 15 Life on land	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
SDG 16 Peace, justice, and strong institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable, and inclusive institutions at all levels
SDG 17 Partnerships for the goals	Strengthen the means of implementation and revitalize the global partnership for sustainable development
NCPs	**Explanation (IPBES, 2019)**
NCP 1 Habitat creation and maintenance	The formation and continued production, by ecosystems, of ecological conditions necessary or favorable for living beings important to humans
NCP 2 Pollination and dispersal of seeds and other propagules	Facilitation by animals of movement of pollen among flowers, and dispersal of seeds, larvae, or spores of organisms beneficial or harmful to humans
NCP 3 Regulation of air quality	Regulation (by impediment or facilitation) by ecosystems, of atmospheric gasses; filtration, fixation, degradation, or storage of pollutants
NCP 4 Regulation of climate	Climate regulation by ecosystems (including regulation of global warming) through effects on emissions of greenhouse gases, biophysical feedbacks, biogenic volatile organic compounds, and aerosols
NCP 5 Regulation of ocean acidification	Regulation, by photosynthetic organisms of atmospheric CO2 concentrations and so seawater pH
NCP 6 Regulation of freshwater quantity, flow, and timing	Regulation, by ecosystems, of the quantity, location, and timing of the flow of surface and groundwater
NCP 7 Regulation of freshwater and coastal water quality	Regulation—through filtration of particles, pathogens, excess nutrients, and other chemicals—by ecosystems of water quality
NCP 8 Formation, protection, and decontamination of soils and sediments	Formation and long-term maintenance of soils including sediment retention and erosion prevention, maintenance of soil fertility, and degradation or storage of pollutants
NCP 9 Regulation of hazards and extreme events	Amelioration, by ecosystems, of the impacts of hazards; reduction of hazards; change in hazard frequency
NCP 10 Regulation of organisms detrimental to humans	Regulation, by ecosystems or organisms, of pests, pathogens, predators, competitors, parasites, and potentially harmful organisms
NCP 11 Energy	Production of biomass-based fuels, such as biofuel crops, animal waste, fuelwood, and agricultural residue

(Continues)

TABLE 1 (Continued)

NCPs	Explanation (IPBES, 2019)
NCP 12 Food and feed	Production of food from wild, managed, or domesticated organisms on land and in the ocean; production of feed
NCP 13 Materials and assistance	Production of materials derived from organisms in cultivated or wild ecosystems and direct use of living organisms for decoration, company, transport, and labor
NCP 14 Medicinal, biochemical, and genetic resources	Production of materials derived from organisms for medicinal purposes; production of genes and genetic information
NCP 15 Learning and inspiration	Opportunities for developing capabilities to prosper through education, knowledge acquisition, and inspiration for art and technological design (e.g., biomimicry)
NCP 16 Physical and psychological experiences	Opportunities for physically and psychologically beneficial activities, healing, relaxation, recreation, leisure, and aesthetic enjoyment based on close contact with nature
NCP 17 Supporting identities	The basis for religious, spiritual, and social-cohesion experiences; sense of place, purpose, belonging, rootedness or connectedness, associated with different entities of the living world; narratives and myths, rituals, and celebrations; satisfaction derived from knowing that a particular landscape, seascape, habitat, or species exist
NCP 18 Maintenance of options	Capacity of ecosystems, habitats, species, or genotypes to keep human options open in order to support a later good quality of life

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" (IPCC, 2019). Both co-benefits and adverse side effects can be biophysical and/or socioeconomic in nature and "are often subject to uncertainty and depend on, among others, local circumstances and implementation practices" (IPCC, 2019). The co-benefits associated with some response options may increase their cost-effectiveness or attractiveness, while adverse side effects might discourage the use of some options, or at the very least, require identification of ways to manage the trade-offs (Bryan et al., 2016). However, managing trade-offs and encouraging co-benefits depend on well-implemented and coordinated activities in appropriate environmental contexts, often requiring institutional and enabling conditions for success and participation of multiple stakeholders (McShane et al., 2011; Reed, Barlow, Carmenta, van Vianen, & Sunderland, 2019). Therefore, it is important to identify these interactions early in decision-making processes, such as through reviews similar to the one presented here.

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). These practices and options were grouped to be broadly applicable in a global assessment, and details of how each practice category was defined and which specific elements the practice entails are found in Smith et al. (2020), table 1; for example, "improved cropland management" includes interventions related to crop improvement, nutrient management, tillage, and water management. Once these categories of practices were assigned and defined, an extensive literature review was conducted to gather evidence on the intersections between each of these 40 practices and the 17 SDGs and 18 NCPs. Literature searches were conducted on Web of Science and Google Scholar to provide a sampling of relevant papers and key interactions; given that we had 1,400 interactions, we did not do a systematic review for each, but rather focused on the most relevant research papers returned by our searches, based on expert assessment.

Each response option was searched with keywords relating to the NCP and SDG in question (see Table 2 for examples). We used open-ended searches rather than ones with detailed SDG and NCP language in order to create a large literature pool (e.g., search terms included "gender" rather than "Sustainable Development Goal 5" or "gender equity"). Because much of the literature does not yet use the term NCP, we also used terminology related to "ecosystem services" in searches and acknowledge that some of the diverse concepts informing NCPs are not yet robust in the literature. Where our initial search did not return key terms in title or abstract, we extended searches to include reference to the body of the paper, to ensure a wide range of papers to initially review for each interaction. Papers varied in terms of scale (from global assessments to local case studies) as well as type of data collected and methods used, given that we drew from a very large pool of scholarly literature incorporating both the natural and social sciences. Authors then applied their expert judgment to review the most relevant papers (e.g., focusing on most cited, those with the widest synthesis such as meta-analyses or global scope, and prestige of outlets). These papers were then read carefully to understand the type and intensity of interactions between response options and the NCP or SDG. Key papers and interactions were then entered into a spreadsheet with reviews conducted individually per cell (Tables S1–S6).

TABLE 2 Examples of search terms and literature found during review

Cell	Search terms	Examples of types of literature	Description of interaction in Supplementary Material	Basis for expert assessment
Agroforestry & SDG 5 (gender equity)	"agroforestry" + "gender" or "women*"	Meta-analysis for Africa (Kiptot, Franzel, & Degrande, 2014) Field studies, East Africa (Gladwin, Peterson, & Uttaro, 2002)	Increased use of agroforestry can benefit female farmers as it requires low overhead (Gladwin et al., 2002), but attention must be paid to land tenure issues (Kiptot & Franzel, 2012; Kiptot et al., 2014)	Literature mostly regional (Africa) but high agreement in studies; however, shows that women have positive benefits on agroforestry rather than agroforestry having benefits on gender equity. *Final assessment*: Medium positive impacts
Risk sharing instruments & NCP 1 (habitat creation)	"risk sharing" or "insurance" or "risk spreading" + "environmental impact" or "ecosystem impact"	National studies of United States based on economic modeling (Goodwin & Smith, 2003; Claassen et al., 2011) Regional (upper Midwest) data from land cover study (Wright & Wimberly, 2013)	Commercial crop insurance often encourages habitat conversion; Wright and Wimberly (2013) found half million 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.	Literature all from the United States but generally in agreement that crop insurance has small negative impact on habitat due to association with crop expansion. *Final assessment*: Small negative impacts
Reduced deforestation and degradation & NCP 9 (regulation of hazards and extreme events)	"Reduced deforestation" or "REDD" or "forest maintenance" + "hazard*" or "extreme event*"	General literature review (Jactel et al., 2017; Locatelli et al., 2015) Field experiments (Cooper-Ellis, Foster, Carlton, & Lezberg, 1999)	Localized hazards like drought, floods, and dust storms can be ameliorated by diverse tree cover, which would be encouraged by reduced deforestation (Cooper-Ellis et al., 1999; Jactel et al., 2017; Locatelli et al., 2015)	Literature mostly about impact of hazards on diverse natural forests rather than direct effect of REDD on hazards per se; reducing deforestation of forest areas leading to improvement in hazard regulation is implied benefit. Also is not a primary goal for most REDD programs. *Final assessment*: Small positive impacts
Improved food processing and retailing & SDG 2 (zero hunger)	"food processing" or "food retail*" or "food chain*" + "hunger" or "malnutrition"	Field-based case studies (Sadler, Gilliland, & Arku, 2013; Stathers, Lamboll, & Myumi, 2013) Systematic literature review (Hollis-Hansen, Vermont, Zafron, Seidman, & Leone, 2019) General literature reviews in multiple disciplines (Bradford et al., 2018; James & James, 2010; Keding, Schneider, & Jordan, 2013; Tirado, Clarke, Jaykus, McQuatters-Gollop, & Frank, 2010; Vermeulen, Campbell, Campbell, & Ingram, 2012)	Improving storage and processing can reduce food waste and health risks associated with poor management practices (Bradford et al., 2018; James & James, 2010; Stathers et al., 2013; Tirado et al., 2010). Improved food processing and supply chains can contribute to more food reaching consumers and improved nutrition (Hollis-Hansen et al., 2019; Keding al., 2013; Vermeulen et al., 2012)	Literature has good global coverage but little quantification of the direct impacts of improved processing/retailing on hunger specifically. Increases in food availability (which indirectly may reduce hunger) is variable most assessed in literature (e.g., Yang & Hanson, 2009), along with the importance of processing to avoid contamination of food chains (which can lead to food deficiencies, e.g., Tirado et al., 2010). *Final assessment*: Medium positive impacts

Given the complications involved in multiple subgoals of some SDGs, as well as inconsistent definitions across some NCPs, our analysis should not be seen as reflecting all possible interactions and reviewing every possible publication, but rather provides an initial broad brush of which interactions appeared most prominent or common in the reviewed literature. The interactions emerging from the literature reviews were then color-coded along a gradient as to small–medium–large positive or negative impact on the NCP/SDG from each specific practice, based on expert evaluation of the literature, such as strength and amount of evidence. Since many interactions could not be quantified, the small to large gradient is meant to be a relative assessment only. Where no interactions appeared in the literature, the cell was left blank.

Some of the SDG and NCP categories assessed may appear similar to each other, such as SDG 13 on "climate action" and NCP 4 on "regulation of climate." However, SDG 13 includes targets for both mitigation and adaptation, so options were weighed by whether they were useful for both. 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" (Díaz et al., 2018). Thus, we evaluated only the relationship between response options and ecosystem impacts on local to global climate for this category.

Furthermore, in assessing both categories of NCPs and SDGs, we were cognizant that the two are different in both kind and in measurement. NCPs refer to processes, goods, and benefits that nature may provide to humans, while SDGs are goals to keep track of the progress expected by UN Parties towards economic, social, and environmental sustainability (Butchart, Miloslavich, Reyers, & Subramanian, 2019). In both cases, there are not always clear measurement standards that are widely agreed upon to determine successful provisioning of NCPs or achievement of some of the SDGs (Hák, Janoušková, & Moldan, 2016; McElwee, 2017). Thus, our reviews are meant to provide a relative sense of the presence or absence of co-benefits and trade-offs, as more detailed interactions were not possible in a review of this type.

For the evaluation process for NCP, we also 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 reduce energy demand, but the "energy" NCP refers specifically to biomass-based fuel provisioning. This necessarily means that the land management options evaluated 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 may lead to land sparing, which has benefits for soils. These are *indirect* impacts on an NCP. (The exception is NCP 6, regulation of ocean acidification, which is by itself an indirect impact. Therefore, any action that directly increases the amount of sequestered carbon is noted.) We focused primarily on *direct* effects in the literature: for example, local seed use preserves local landraces, which *directly* contributes to the NCP "maintenance of options." Therefore, the interactions we assessed should be considered a conservative estimation of effects; there are likely many more secondary and indirect effects, but they are too difficult to assess, or the literature is not yet complete or conclusive. Furthermore, many NCP may trade-off against one another, as supply of one NCP might lead to less availability of another (Rodríguez et al., 2006); for example, use of ecosystems to produce bioenergy will likely lead to decreases in water availability if mono-cropped high-intensity plantations are used (Gasparatos, Stromberg, & Takeuchi, 2011). These interactions and trade-offs *between* NCPs are not mapped directly in our assessment.

For our analysis of SDG interactions, the literature was particularly uneven. Because many land management options only produce indirect or multidirectional effects on SDGs, we indicate where directionality of impacts is mixed or unclear. As a result, the value chain and risk management options appear to offer more direct benefits for SDGs. Furthermore, some SDGs 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 transfer to trade openness). Some SDG targets are clear and well defined (such as SDG 1 on eliminating extreme poverty), while other goals are about processes and interactions which make targets and indicators more challenging (e.g., SDG 13 on climate action which discusses the need to strengthen resilience and integrate climate policies into multiple sectors, but has no specific mitigation target; Campbell et al., 2018). We attempted to conduct literature searches for key indicators per SDG but found some more well represented in the literature than others.

Additionally, like NCPs, SDG goals are often interdependent in both positive and negative ways, with both synergies and trade-offs possible as outcomes (Campbell et al., 2018; Pradhan, Costa, Rybski, Lucht, & Kropp, 2017; Singh et al., 2018). For example, achieving SDG 15 on terrestrial ecosystem management might well provide co-benefits with SDG 3 on good health, such as through improved access to forest foods (Rowland, Ickowitz, Powell, Nasi, & Sunderland, 2017), and carbon sequestration to reach SDG 13 on climate action (Timko et al., 2018). Achieving some SDGs might make progress on others more difficult; for example, SDG 9 to increase industrialization and infrastructure and SDG 15 to improve life on land may conflict, as more industrialization is likely to lead to increased resource demands with negative effects on habitats (Nilsson et al., 2018). Therefore, a positive association on one SDG measure might be directly correlated with a negative measure on another. The specific caveats on each of these interactions can be found in the supplementary material tables.

3 | RESULTS

In the sections below, we provide the primary interactions arising from the literature review and represent them visually in Tables 3–8, while the textual descriptions of interactions and literature reviewed can be found in Tables S1–S6. In all tables, colors represent the direction of impact: positive (blue) or negative (brown), and the relative scale of the impact (dark colors for large impacts to light colors for smaller impacts). The supplementary material tables include brief explanations of directionality of interactions with specific references. Blank cells represent a finding of no evidence of an interaction and/

TABLE 3 Impacts on Nature's Contributions to People of integrated response options based on land management

Integrated response options based on land management	NCP 1 Habitat creation & maintenance	NCP 2 Pollination and dispersal of seeds and other propagules	NCP 3 Regulation of air quality	NCP 4 Regulation of climate	NCP 5 Regulation of ocean acidification	NCP 6 Regulation of freshwater quantity, flow and timing	NCP 7 Regulation of freshwater and coastal water quality	NCP 8 Formation, protection and decontamination of soils & sediments	NCP 9 Regulation of hazards & extreme events	NCP 10 Regulation of organisms detrimental to humans	NCP 11 Energy	NCP 12 Food and feed	NCP 13 Materials and assistance	NCP 14 Medicinal, biochemical and genetic resources	NCP 15 Learning and inspiration	NCP 16 Physical and psychological experiences	NCP 17 Supporting identities	NCP 18 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																		
Improved and sustainable forest management																		
Reduced deforestation and degradation																		
Reforestation and forest restoration																		
Afforestation																		
Increased soil organic carbon content																		
Reduced soil erosion																		
Reduced soil salinization																		
Reduced soil compaction																		
Biochar addition to soil																		

(Continues)

TABLE 3 (Continued)

Integrated response options based on land management	NCP 1 Habitat creation & maintenance	NCP 2 Pollination and dispersal of seeds and other propagules	NCP 3 Regulation of air quality	NCP 4 Regulation of climate	NCP 5 Regulation of ocean acidification	NCP 6 Regulation of freshwater quantity, flow and timing	NCP 7 Regulation of freshwater and coastal water quality	NCP 8 Formation, protection and decontamination of soils & sediments	NCP 9 Regulation of hazards & extreme events	NCP 10 Regulation of organisms detrimental to humans	NCP 11 Energy	NCP 12 Food and feed	NCP 13 Materials and assistance	NCP 14 Medicinal, biochemical and genetic resources	NCP 15 Learning and inspiration	NCP 16 Physical and psychological experiences	NCP 17 Supporting identities	NCP 18 Maintenance of options
Fire management	Medium positive	Small positive	Medium positive	Large positive	Large positive	Small positive	Small positive	Small positive	Large positive	Small positive	Small positive					Small positive		
Reduced landslides and natural hazards	Small positive					Small positive	Small positive	Small positive	Large positive			Small positive						
Reduced pollution including acidification	Medium positive	Small positive	Medium positive	Medium positive	Medium positive		Large positive	Small positive										
Management of invasive species / encroachment	Medium positive	Small positive				Small positive	Small positive	Small positive		Small positive		Small positive	Small negative					Medium positive
Restoration and avoided conversion of coastal wetlands	Large positive	Medium positive		Large positive	Large positive	Large positive	Large positive	Large positive	Large positive	Small positive		Variable		Small positive	Small positive	Small positive	Small positive	Medium positive
Restoration and avoided conversion of peatlands	Large positive	Small positive	Medium positive	Medium positive	Medium positive	Large positive	Large positive	Large positive		Small positive	Small negative	Small negative	Small negative		Small positive	Small positive	Small positive	Small positive
Biodiversity conservation	Large positive	Large positive	Small positive	Medium positive	Medium positive	Small positive	Small positive	Large positive	Medium positive	Small positive		Variable	Variable	Large positive	Large positive	Large positive	Large positive	Large positive
Enhanced weathering of minerals				Large positive	Large positive		Small negative	Small positive				Small positive						
Bioenergy and BECCS[a]	Large negative	Small negative	Medium positive	Large positive	Large positive	Large negative	Variable	Medium negative			Large positive	Large negative	Small negative	Small negative	Small negative	Small negative	Small negative	Small negative

LEGEND

No data to establish relationship	Large positive impacts	Medium positive impacts	Small positive impacts	Small negative impacts	Medium negative impacts	Large negative impacts	Variable impacts, can be both positive and negative depending on context
No color							

[a]Note that this refers to large areas of bioenergy crops capable of producing large mitigation benefits (>3 $GtCO_2$/year). 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).

TABLE 4 Impacts on Nature's Contributions to People of integrated response options based on value chain management

Integrated response options based on value chain management	NCP 1 Habitat creation & maintenance	NCP 2 Pollination and dispersal of seeds and other propagules	NCP 3 R egulation of air quality	NCP 4 Regulation of climate	NCP 5 Regulation of ocean acidification	NCP 6 Regulation of freshwater quantity, flow and timing	NCP 7 Regulation of freshwater and coastal water quality	NCP 8 Formation, protection and decontamination of soils & sediments	NCP 9 Regulation of hazards and extreme events	NCP 10 Regulation of organisms detrimental to humans	NCP 11 Energy	NCP 12 Food and feed	NCP 13 M aterials and assistance	NCP 14 Medicinal, biochemical and genetic resources	NCP 15 Learning and inspiration	NCP 16 Physical and psychological experiences	NCP 17 Suppo rting identities	NCP 18 M aintenance of options
Dietary change	Medium positive	Small positive		Large positive	Large positive	Small positive	Small positive					Large positive						
Reduced post-harvest losses	Medium positive			Large positive	Large positive	Small positive	Small positive			Medium positive		Large positive						
Reduced food waste (consumer or retailer)	Medium positive			Large positive	Large positive	Small positive	Small positive					Large positive						
Material substitution	Small negative			Small positive	Small positive								Large positive					
Sustainable sourcing	Small positive		Small positive			Small positive	Small positive				Small positive	Variable	Medium positive	Small positive			Variable	
Management of supply chains			Small positive									Medium positive	Small positive					
Enhanced urban food systems	Small positive	Small positive	Small positive			Small negative	Small negative					Large positive	Small positive	Small positive	Small positive	Small positive	Small positive	Small positive
Improved food processing and retail			Small positive			Small positive						Medium positive						
Improved energy use in food systems			Small positive	Small positive	Small positive													

LEGEND

No data to establish relationship	Large positive impacts	Medium positive impacts	Small positive impacts	Small negative impacts	Medium negative impacts	Large negative impacts	Variable impacts, can be both positive and negative depending on context
No color							

TABLE 5 Impacts on Nature's Contributions to People of integrated response options based on risk management

Integrated response options based on risk management	NCP 1 Habitat creation & maintenance	NCP 2 Pollination and dispersal of seeds and other propagules	NCP 3 Regulation of air quality	NCP 4 Regulation of climate	NCP 5 Regulation of ocean acidification	NCP 6 Regulation of freshwater quantity, flow and timing	NCP 7 Regulation of freshwater and coastal water quality	NCP 8 Formation, protection and decontamination of soils & sediments	NCP 9 Regulation of hazards and extreme events	NCP 10 Regulation of organisms detrimental to humans	NCP 11 Energy	NCP 12 Food and feed	NCP 13 Materials and assistance	NCP 14 Medicinal, biochemical and genetic resources	NCP 15 Learning and inspiration	NCP 16 Physical and psychological experiences	NCP 17 Supporting identities	NCP 18 Maintenance of options
Management of urban sprawl	Medium positive	Small positive	Large positive			Large positive	Large positive	Large positive	Medium positive			Medium positive						
Livelihood diversification												Small positive	Small positive					
Use of local seeds	Small positive	Medium positive				Small positive	Small positive	Small positive		Large positive		Variable	Small positive	Medium positive	Large positive		Large positive	Large positive
Disaster risk management	Small positive								Large positive			Medium positive						
Risk sharing instruments	Small negative	Small negative		Small negative			Small negative	Medium negative		Small negative		Large positive		Small negative				Small negative

LEGEND

No data to establish relationship	Large positive impacts	Medium positive impacts	Small positive impacts	Small negative impacts	Medium negative impacts	Large negative impacts	Variable impacts, can be both positive and negative depending on context
No color							

TABLE 6 Impacts on the UN SDG of integrated response options based on land management

Integrated response options based on land management	SDG 1 No poverty	SDG 2 Zero hunger	SDG 3 Good health and well-being	SDG 4 Quality education	SDG 5 Gender equality	SDG 6 Clean water and sanitation	SDG 7 Affordable and clean energy	SDG 8 Decent work and economic growth	SDG 9 Industry, innovation and infrastructure	SDG 10 Reduced inequality	SDG 11 Sustainable cities and communities	SDG 12 Responsible consumption and production	SDG 13 Climate action	SDG 14 Life below water	SDG 15 Life on land	SDG 16 Peace and justice and strong institutions	SDG 17 Partnerships to achieve the goal
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																	
Improved and sustainable forest management																	
Reduced deforestation and degradation																	
Reforestation and forest restoration																	
Afforestation																	
Increased soil organic carbon content																	
Reduced soil erosion																	
Reduced soil salinization																	
Reduced soil compaction																	
Biochar addition to soil																	

(Continues)

TABLE 6 (Continued)

Integrated response options based on land management	SDG 1 No poverty	SDG 2 Zero hunger	SDG 3 Good health and well-being	SDG 4 Quality education	SDG 5 Gender equality	SDG 6 Clean water and sanitation	SDG 7 Affordable and clean energy	SDG 8 Decent work and economic growth	SDG 9 Industry, innovation and infrastructure	SDG 10 Reduced inequality	SDG 11 Sustainable cities and communities	SDG 12 Responsible consumption and production	SDG 13 Climate action	SDG 14 Life below water	SDG 15 Life on land	SDG 16 Peace and justice and strong institutions	SDG 17 Partnerships to achieve the goal
Fire management			Large positive			Small positive					Medium positive		Large positive		Large positive		
Reduced landslides and natural hazards	Small positive	Small positive	Medium positive								Small positive		Medium positive		Small positive		
Reduced pollution including acidification			Large positive			Medium positive			Small positive		Small positive		Small positive	Small positive	Small positive		
Management of invasive species / encroachment	Small positive	Small positive	Small positive			Medium positive		Small positive					Small positive		Medium positive		
Restoration and avoided conversion of coastal wetlands	Variable	Variable	Variable			Large positive		Small positive	Variable				Large positive	Large positive	Large positive		
Restoration and avoided conversion of peatlands	Small negative	Small negative	Medium positive			Large positive	Small negative	Small negative					Medium positive		Large positive		
Biodiversity conservation	Variable	Variable	Medium positive		Variable	Medium positive	Variable	Variable	Small negative		Medium positive		Large positive	Large positive	Large positive	Variable	Small positive
Enhanced weathering of minerals						Small negative			Small positive				Small positive				
Bioenergy and BECCS[a]	Variable	Large negative	Variable			Medium negative	Large positive	Small positive	Small positive			Small positive	Variable		Large negative		

LEGEND

No data to establish relationship	Large positive impacts	Medium positive impacts	Small positive impacts	Small negative impacts	Medium negative impacts	Large negative impacts	Variable impacts, can be both positive and negative depending on context
No color	(dark teal)	(teal)	(light cyan)	(light pink)	(light salmon)	(orange)	(hatched)

[a]Note that this refers to large areas of bioenergy crops capable of producing large mitigation benefits (>3 $GtCO_2$/year). The effect of bioenergy and BECCS on SDGs is scale and context dependent, and smaller scale and more sustainable bioenergy would lessen these negative impacts (IPCC, 2019).

TABLE 7 Impacts on the UN SDG of integrated response options based on value chain interventions

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

LEGEND

No data to establish relationship	Large positive impacts	Medium positive impacts	Small positive impacts	Small negative impacts	Medium negative impacts	Large negative impacts	Variable impacts, can be both positive and negative depending on context
No color							

TABLE 8 Impacts on the UN SDG of integrated response options based on risk management

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

LEGEND

No data to establish relationship	Large positive impacts	Medium positive impacts	Small positive impacts	Small negative impacts	Medium negative impacts	Large negative impacts	Variable impacts, can be both positive and negative depending on context
No color							

TABLE 9 Interactions between Nature's Contributions to People (NCPs) for two response options

NCP	Bioenergy and BECCS	Use of local seeds
NCP 1 Habitat creation and maintenance	Can reduce areas of natural habitat with negative effects on biodiversity (Hof et al., 2018; Immerzeel, Verweij, van der Hilst, & Faaij, 2014)	Use of commercial seeds can contribute to habitat loss through agricultural expansion and intensification; local seeds likely better (Upreti & Upreti, 2002)
NCP 2 Pollination and dispersal of seeds and other propagules	If natural habitats are decreased due to bioenergy expansion, would reduce natural pollinators (Keitt, 2009)	Use of open pollinated seeds is beneficial for pollinators and creates political will to conserve them (Helicke, 2015)
NCP 3 Regulation of air quality	The use of BECCS could reduce air pollution from use of fossil fuels (IPCC, 2018)	N/A
NCP 4 Regulation of climate	Large mitigation potential depending on scale, for example, up to ~11 $GtCO_2eq$/year (IPCC, 2018; Smith et al., 2020); any local and regional climate effects would be dependent on feedstock, prior land use, scale, and location	N/A
NCP 5 Regulation of ocean acidification	Bioenergy and BECCS will reduce ocean acidification by reducing CO_2 emissions and concentrations (Doney, Fabry, Feely, & Kleypas, 2009; IPCC, 2018)	N/A
NCP 6 Regulation of freshwater quantity, flow, and timing	Depending on the feedstock, can require water. Models show high risk of water scarcity if BECCS is deployed on widespread scale (Hejazi et al., 2014; Popp, Dietrich, et al., 2011; Smith, Davis, et al., 2016) through both increases in water withdrawals (Bonsch et al., 2015; Hejazi et al., 2014) and changes in surface runoff (Cibin, Trybula, Chaubey, Brouder, & Volenec, 2016)	Local seeds often have lower water demands as they are suited to local environments (Adhikari, 2014)
NCP 7 Regulation of freshwater and coastal water quality	Bioenergy can affect freshwater quality via changes in nitrogen runoff from fertilizer 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, Eheart, Cai, & Miguez, 2010) and others showing declines (Sinha, Michalak, Calvin, & Lawrence, 2019)	Likely to contribute to less pollution as local seeds are usually grown organically (Adhikari, 2014)
NCP 8 Formation, protection, and decontamination of soils and sediments	Will likely decrease soil quality if exotic fast-growing trees used (Humpenöder et al., 2018; Stoy et al., 2018)	Likely to contribute to better soils as local seeds are usually grown organically and with lower tillage (Adhikari, 2014)
NCP 9 Regulation of hazards and extreme events	N/A	N/A
NCP 10 Regulation of organisms detrimental to humans	N/A	Local seeds often need less pesticides thereby reducing pest resistance (Adhikari, 2014)
NCP 11 Energy	BECCS and biofuels can contribute up to 300 EJ of primary energy by 2100 (Clarke et al., 2014)	N/A
NCP 12 Food and feed	Large-scale deployment of bioenergy and BECCS can lead to significant trade-offs with food production and significantly higher food prices given large-scale land conversion (Humpenöder et al., 2018; Popp et al., 2017; Smith, Davis, et al., 2016)	Local seeds can lead to more diverse and healthy food in areas with strong food sovereignty networks (Bisht et al., 2018; Coomes et al., 2015). However, local seeds often are less productive than improved commercial varieties
NCP 13 Materials and assistance	If bioenergy and BECCS drive land use conversion (Clarke et al., 2014; Humpenöder et al., 2018; Popp et al., 2017; Smith, Davis, et al., 2016), it can reduce opportunities for production of other materials	Local seeds can produce multifunctional materials (Adhikari, 2014)
NCP 14 Medicinal, biochemical, and genetic resources	If bioenergy and BECCS drive land use conversion (Clarke et al., 2014; Humpenöder et al., 2018; Popp et al., 2017; Smith, Davis, et al., 2016), it can reduce genetic resources	Many local seeds can have multiple functions, including producing medicinals (Hammer & Teklu, 2008)

(Continues)

TABLE 9 (Continued)

NCP	Bioenergy and BECCS	Use of local seeds
NCP 15 Learning and inspiration	If bioenergy and BECCS drive land use conversion (Clarke et al., 2014; Humpenöder et al., 2018; Popp et al., 2017; Smith, Davis, et al., 2016), it can reduce opportunities for learning and inspiration	Passing on seed information is important cultural learning process (Coomes et al., 2015)
NCP 16 Physical and psychological experiences	If bioenergy and BECCS drive land use conversion (Clarke et al., 2014; Humpenöder et al., 2018; Popp et al., 2017; Smith, Davis, et al., 2016), it can reduce opportunities for recreation & tourism	N/A
NCP 17 Supporting identities	If bioenergy and BECCS drive land use conversion (Clarke et al., 2014; Humpenöder et al., 2018; Popp et al., 2017; Smith, Davis, et al., 2016), it can reduce culturally significant landscapes	Seeds associated with specific cultural identities for many (Coomes et al., 2015)
NCP 18 Maintenance of options	If bioenergy and BECCS drive land use conversion (Clarke et al., 2014; Humpenöder et al., 2018; Popp et al., 2017; Smith, Davis, et al., 2016), it can reduce genetic diversity	Food sovereignty movements have promoted saving of genetic diversity of crops through on-farm maintenance (Isakson, 2009)

or no literature. In cases where there are both positive and negative interactions and the literature is uncertain about the overall impact, hashing 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 material tables for the specific caveats that may apply.

3.1 | Interactions of the options on NCP supply

Tables 3–5 summarize the impacts of the response options on NCP supply. Overall, several of the assessed response options stand out as having co-benefits across 10 or more NCPs with no adverse impacts on ecosystems: *improved cropland management*, *agroforestry*, *increased soil organic carbon content*, and *fire management*. Several options had mostly positive effects for 10 or more NCPs but some multidirectional interactions on others: *improved and sustainable forest management*, *reduced deforestation and degradation*, *reforestation and forest restoration*, *restoration and avoided conversion of coastal wetlands*, *biodiversity conservation*, and *use of local seeds*. Examples of co-benefits between response options and NCPs include positive impacts on habitat maintenance (NCP 1) from practices 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 defenses (Lin, 2011), while invasive species management has strong direct links to improved habitats and ecosystem diversity (Richardson & Wilgen, 2004).

Other response options may have strengths in some NCP but require trade-offs with others. For example, afforestation may bring many positive benefits for climate mitigation and biomass energy production but may trade-off with food production and water quantity. Many of the interactions are scale and context dependent; for example, large-scale afforestation of monocrop trees on water-scarce croplands would have negative effects (Kreidenweis et al., 2016), while well-managed small-scale afforestation on unused or degraded lands could have mostly beneficial effects (Yao & Li, 2010). Several response options, including afforestation, bioenergy and bioenergy with carbon capture and storage (BECCS), and some risk sharing instruments, like commercial crop insurance, can have significant negative consequences across multiple NCPs, but again, are dependent on scale and context. While BECCS may deliver large co-benefits for climate mitigation, it can result in a number of adverse impacts that are significant with regard to water provisioning, food and feed availability, and loss of supporting identities if BECCS competes against local land uses (Calvin et al., 2014; Stoy et al., 2018).

3.2 | Interactions of the options with SDGs

Tables 6–8 summarize the impact of the response options on the SDGs. Overall, several response options have co-benefits across 10 or more SDGs with no adverse side effects on any SDG: *improved grazing land management*, *agroforestry*, *integrated water management*, *reduced post-harvest losses*, and *disaster risk management*. Several options have mostly positive effects for 10 or more SDGs but some multidirectional interactions or one negative on others: *improved and sustainable forest management*, *sustainable sourcing*, *enhanced urban food systems*, *management of urban sprawl*, and *use of local seeds*. For example, on the latter option, use of local seeds can bring positive social benefits for poverty and hunger reduction, but may reduce potentials for international trade (SDG 17; Kloppenburg, 2014). Other response options like enhanced urban food systems and management of urban sprawl 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 (Badami & Ramankutty, 2015; Brueckner, 2000).

Some of the prominent synergies between response options and SDGs in the literature include positive poverty reduction

TABLE 10 Interactions between Sustainable Development Goals (SDGs) and two response options

SDG	Bioenergy and BECCS	Use of local seeds
SDG 1 No poverty	Bioenergy production could create jobs but could also compete for land with alternative uses (Clarke et al., 2014; Humpenöder et al., 2018; Popp et al., 2017; Smith, Davis, et al., 2016). Therefore, bioenergy could have positive or negative effects on poverty rates among smallholders, among other social effects (Dooley & Kartha, 2018; IPCC, 2018)	Many hundreds of millions of smallholders still rely on local seeds; without them, they would have to find money to buy commercial seeds (Altieri, Funes-Monzote, & Petersen, 2012; Howard, 2015; McGuire & Sperling, 2016)
SDG 2 Zero hunger	Biofuel plantations may lead to decreased food security through competition for land. Large-scale deployment of bioenergy and BECCS can lead to significant trade-offs with food production (Humpenöder et al., 2018; IPCC, 2018; Popp, Lotze-Campen, et al., 2011; Smith, Haszeldine, & Smith, 2016)	Local seeds revive and strengthen local food systems (McMichael & Schneider, 2011) and lead to more diverse and healthy food in areas with strong food sovereignty networks (Bisht et al., 2018; Coomes et al., 2015). However, local seeds often are less productive than improved varietie
SDG 3 Good health and well-being	BECCS could have positive effects through improvements in air quality (IPCC, 2018), but bioenergy and BECCS could have negative effects on health and well-being through impacts on food systems and water (Burns & Nicholson, 2017; Humpenöder et al., 2018)	Local seed use is associated with fewer pesticides (Altieri et al., 2012); loss of local seeds and substitution by commercial seeds is perceived by farmers to increase health risks (Mazzeo & Brenton, 2013), although overall literature on links between food sovereignty and health is weak (Jones, Shapiro, & Wilson, 2015)
SDG 4 Quality education	N/A	N/A
SDG 5 Gender equality	N/A	Women play important roles in preserving and using local seeds (Bezner Kerr, 2013; Ngcoya & Kumarakulasingam, 2017) and sovereignty movements paying more attention to gender needs (Park, White, & Julia, 2015)
SDG 6 Clean water and sanitation	Depending on the feedstock, can require water. Models show high risk of water scarcity if BECCS is deployed on widespread scale (Hejazi et al., 2014; Popp, Dietrich, et al., 2011; Smith, Davis, et al., 2016) through both increases in water withdrawals (Bonsch et al., 2015; Hejazi et al., 2014; IPCC, 2018) and changes in surface runoff (Cibin et al., 2016)	Local seeds often have lower water demands, as well as less use of pesticides that can contaminate water (Adhikari, 2014)
SDG 7 Affordable and clean energy	Bioenergy and BECCS can contribute up to 300 EJ of primary energy by 2100 (Clarke et al., 2014); bioenergy can provide clean, affordable energy (IPCC, 2018)	N/A
SDG 8 Decent work and economic growth	Access to clean, affordable energy will help economic growth (IPCC, 2018)	Food sovereignty supporters believe protecting smallholder agriculture provides more employment than commercial agriculture (Kloppenberg, 2010), although exact numbers unknown
SDG 9 Industry, innovation, and infrastructure	BECCS will require development of new technologies (Smith, Haszeldine, & Smith, 2016)	N/A
SDG 10 Reduced inequality	N/A	Seed sovereignty advocates believe it will contribute to reduced inequality (Park et al., 2015; Wittman, 2011), but there is inconclusive empirical evidence
SDG 11 Sustainable cities and communities	N/A	Seed sovereignty can help sustainable urban gardening (Demailly & Darly, 2017) which can be part of a sustainable city by providing fresh, local food (Leitgeb, Schneider, & Vogl, 2016)
SDG 12 Responsible consumption and production	Switching to bioenergy reduces depletion of finite resources (IPCC, 2018)	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., 2015; Van Niekerk & Wynberg, 2017)

(Continues)

TABLE 10 (Continued)

SDG	Bioenergy and BECCS	Use of local seeds
SDG 13 Climate action	Large mitigation potential depending on scale, for example, up to ~11 $GtCO_2eq$/year (IPCC, 2018; Smith et al., 2020), but potentially large negative adaptation effects due to land competition (Dooley & Kartha, 2018; Fuss et al., 2016; Humpenöder et al., 2018)	Local seeds tend to be resilient to different climate hazards and thus can enhance adaptation (Louwaars, 2002; Santilli, 2012)
SDG 14 Life below water	Bioenergy and BECCS will reduce ocean acidification by reducing CO_2 emissions and concentrations (Doney et al., 2009; IPCC, 2018)	N/A
SDG 15 Life on land	Can reduce areas of natural habitat with negative effects on biodiversity (Hof et al., 2018; Immerzeel et al., 2014; IPCC, 2018)	Use of commercial seeds can contribute to habitat loss through agricultural expansion and intensification; local seeds likely better (Upreti & Upreti, 2002)
SDG 16 Peace and justice and strong institutions	N/A	Seed sovereignty is positively associated with strong local food movements, which contribute to social capital (Coomes et al., 2015; Grey & Patel, 2015; McMichael & Schneider, 2011)
SDG 17 Partnerships to achieve the goal	N/A	Seed sovereignty could be seen as threat to free trade and imports of genetically modified seeds (Howard, 2015; Kloppenberg, 2010; Kloppenburg, 2014)

impacts (SDG 1) from activities like improved water management or better 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 (Bezner Kerr, 2013; Ngcoya & Kumarakulasingam, 2017).

Other response options may help to deliver some SDGs but create multiple trade-offs with others, such as dietary change. Several response options, including avoidance of grassland conversion, reduced deforestation and degradation, reforestation and forest restoration, afforestation, and restoration and avoided conversion of peatlands potentially have trade-offs across multiple SDGs primarily as they prioritize land health over food production (Crooks, Herr, Tamelander, & Laffoley, 2011). Some response options, such as afforestation, biochar, and bioenergy and BECCS, will likely involve trade-offs over multiple SDGs with potentially significant adverse consequences (Bowman & Zilberman, 2013; Burns & Nicholson, 2017; Locatelli, Pavageau, Pramova, & Di Gregorio, 2015).

3.3 | Case studies of interactions

The supplementary material tables provide over 1,400 specific interactions that were assessed. To provide a flavor of what these review outcomes indicate, we note below for two options what the types and directionality of interactions found in the literature were (Tables 9 and 10). Bioenergy and BECCS and use of local seeds present a contrast, in that the literature on bioenergy/BECCS is mostly based on modelling studies (since this option is in limited operation), while the literature on local seeds is primarily based on local or regional case studies.

For the review of bioenergy/BECCS, we find that the literature on interactions with other land uses is fairly robust, with concerns about the impacts on important NCPs like habitats and biodiversity, water quantity, and soil quality reflected in models (Table 9). However, the literature on non-tangible NCPs, like learning or identities, is less direct; there, negative impacts are assumed rather than known, and based on impacts of land use change. For SDGs, we find conflicting evidence of the impact of BECCS on poverty and good health, while negative impacts on food security are strongly implied; such impacts trade-off with the potential for BECCS to make positive contributions to innovation, energy use, and climate mitigation (Table 10). In our review of use of local seeds, we find that the literature on NCP interactions is fairly thin, with a few key studies providing some indications of interactions, while the literature on SDG interactions is wider, with reports noting that use of noncommercial seeds can bring economic and social benefits, particularly in urban settings, and for women (Table 10). In both examples, there remain gaps in the literatures reviewed.

3.4 | Identifying patterns of co-benefits and trade-offs

Overall, across both categories of SDGs and NCPs, 15 of 40 options that were evaluated deliver at least some co-benefits with no identified negative side effects or trade-offs for the full range of NCPs and SDGs (Table 11, blue shading). This includes many agriculture- and soil-based land management options, some ecosystem-based land management options, reduced post-harvest

TABLE 11 Patterns of co-benefits and negative impacts across options

	Positive co-benefits for NCPs	Positive co-benefits for SDGs	Negative impacts for NCPs	Negative impacts for SDGs	Multidirectional NCP interactions	Multidirectional SDG interactions
Increased food productivity	5	11	1		4	1
Improved cropland management	11	9				
Improved grazing land management	9	10				
Improved livestock management	7	8				
Agroforestry	16	11				
Agricultural diversification	9	7				1
Avoidance of conversion of grassland to cropland	7	3	1	3		
Integrated water management	9	15				
Improved and sustainable forest management	15	11			3	2
Reduced deforestation and degradation	14	5		3	4	4
Reforestation and forest restoration	14	7		2	4	3
Afforestation	7	5	4	3	6	3
Increased soil organic carbon content	10	8				
Reduced soil erosion	7	7				
Reduced soil salinization	5	6				
Reduced soil compaction	6	6				
Biochar addition to soil	6	2	2	3	1	1
Fire management	12	5				
Reduced landslides and natural hazards	6	6				
Reduced pollution including acidification	7	7				
Management of invasive species/ encroachment	8	7	1			
Restoration and avoided conversion of coastal wetlands	14	5			1	4
Restoration and avoided conversion of peatlands	13	4	3	4		
Biodiversity conservation	15	7		1	2	6
Enhanced weathering of minerals	4	2	1	1		
Bioenergy and BECCS	4	4	11	3	1	3
Dietary change	7	9		3		
Reduced post-harvest losses	7	12				
Reduced food waste (consumer or retailer)	6	10		2		1
Material substitution	3	5	1	3		1
Sustainable sourcing	7	12			2	2
Management of supply chains	3	11		2		
Enhanced urban food systems	10	14	2	1		
Improved food processing & retail	3	10		2		1
Improved energy use in food systems	3	7				
Management of urban sprawl	8	12		1		

(Continues)

TABLE 11 (Continued)

	Positive co-benefits for NCPs	Positive co-benefits for SDGs	Negative impacts for NCPs	Negative impacts for SDGs	Multidirectional NCP interactions	Multidirectional SDG interactions
Livelihood diversification	2	7				3
Use of local seeds	11	11		1	1	1
Disaster risk management	3	15				
Risk sharing instruments	1	6	8	2		4

Notes: Columns are sums of categories of co-benefits and adverse side effects from Tables 3 to 8 and do not indicate the magnitude of the effect.
Blue indicates the presence of co-benefits with no noted adverse side effects.
Brown indicates the presence of multiple adverse side effects across both SDGs and NCPs.
Red text indicates presence of potentially negative trade-off.
Grey text indicates multidirectional impacts.

losses, improved energy use in food systems, and disaster risk management. Only five options (afforestation, biochar, avoided peatland conversion, bioenergy and BECCS, and some types of risk sharing instruments, such as crop insurance) have potentially negative impacts on five or more NCPs and SDGs combined (Table 11, brown shading). However, this comparison is meant only to give relative sense of potential adverse side effects, as the caveat stands that one positive co-benefit is not necessarily equal to one negative impact; the magnitude of effects varies widely depending on context.

3.5 | Combining NCPs and SDGs with other societal goals

Our findings of co-benefits and adverse side effects associated with a range of response options should also be combined with attention to how effectively the response options deliver across other key objectives such as climate change mitigation, climate change adaptation, land degradation and desertification, or food security. Smith et al. (2020) assessed the same 40 options against these specific challenges in a quantitative manner and found that nine of the options delivered medium to large benefits for all four land challenges. The options that stood out were *increased food productivity*, *improved cropland management*, *improved grazing land management*, *improved livestock management*, *agroforestry*, *improved and sustainable forest management*, *increased soil organic carbon content*, *fire management* and *reduced post-harvest losses*. Of these nine options, however, our analysis here showed potential adverse side effects on either the SDGs or NCPs for two options: increased food productivity (associated with potential NCP trade-offs around water and soil quality and beneficial pollinators and harmful pests) and improved and sustainable forest management (associated with the potential for NCP trade-offs around food production and hazard mitigation, and SDG trade-offs around poverty reduction and food production).

Looking only at response options that deliver the highest mitigation benefits, five options of the 40 have large potential (>3 $GtCO_2eq$/year) without adverse impacts on the other land challenges, according to Smith et al. (2020): *increased food productivity, reduced deforestation and degradation, increased soil organic carbon content*, *fire management* and *reduced post-harvest losses*. Of these, only three (*increased soil organic carbon content*, *fire management*, and *reduced post-harvest losses*) were not associated with some potential negative side effects on either SDGs or NCPs in our analysis.

Sixteen practices that were evaluated had large climate adaptation potential, positively benefiting more than 25 million people a year, without adverse consequences for other land challenges: *increased food productivity*, *improved cropland management*, *agroforestry*, *agricultural diversification*, *improved and sustainable 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* (Smith et al., 2020). However, of these 16 options, more than half of them (9) do show potential trade-offs with either NCPs or SDGs in our analysis.

4 | DISCUSSION

Decision-makers are increasingly asking for policy options that will help them achieve agreed-upon global goals like the Paris Agreement and the SDGs in an integrated manner (Sachs et al., 2019). Many land challenges in particular can be met with a range of response options readily available, such as reducing the conversion of natural ecosystems or increasing soil carbon content using basic technologies like cover crops and changing tillage and residue management. Assessing these options against their co-benefits and adverse side effects can help policymakers to account for impacts on both natural and human systems. Our assessment using an extended literature review has been as comprehensive as possible (40 options times 18 NCPs and 17 SDGs) and robust (literature in the thousands of documents) to provide some direction to such policymaking and goal setting. Below we discuss the primary findings, limitations of the study, and some future research directions.

TABLE 12 Highlighting response options for individual Sustainable Development Goals (SDGs)

SDGs	Response options with large positive impacts for this goal [and potential trade-offs (TO)]
SDG 1 No poverty	**Integrated water management, increased soil organic carbon, disaster risk management** *High positive impact on this SDG but comes with potential trade-offs:* **Increased food productivity** (*TO with NCP2, NCP 6, NCP7, NCP8, NCP 10, & SDG 14*), a**gricultural diversification** (*TO with SDG 10*), **management of supply chains** (*TO with SDG 6 & SDG 7*), **livelihood diversification** *(TO with SDG 4, SDG 5, & SDG 10)*
SDG 2 Zero hunger	**Agroforestry, integrated water management, increased soil organic carbon, reduced soil erosion, reduced salinization, reduced soil compaction, reduced post-harvest losses, disaster risk management** *High positive impact on this SDG but comes with potential trade-offs:* **Increased food productivity** (*TO with NCP2, NCP 6, NCP7, NCP8, NCP 10, & SDG 14*), **agricultural diversification** *(TO with SDG 10)*, **dietary change** (*TO with SDG 1, SDG 7 & SDG 14*), **management of supply chains** (*TO with SDG 6 and SDG7*), **enhanced urban food systems** (*TO with NCP 6, NCP 7, & SDG 6*)
SDG 3 Good health and well-being	**Integrated water management, fire management, reduced pollution, reduced post-harvest losses, disaster risk management** *High positive impact on this SDG but comes with potential trade-offs:* **Increased food productivity** (*TO with NCP2, NCP 6, NCP7, NCP8, NCP 10, & SDG 14*), **dietary change** (*TO with SDG 1, SDG 7, & SDG 14*), **management of supply chains** (*TO with SDG 6 and SDG7*), **management of urban sprawl** (*TO with SDG 8*), **livelihood diversification** *(TO with SDG 4, SDG 5, & SDG 10)*
SDG 4 Quality education[a]	**Disaster risk management** *Medium positive impact on this SDG but comes with potential trade-offs:* **risk sharing instruments** (*TO with NCP 1, NCP 2, NCP 4, NCP 7, NCP 8, NCP 10, NCP 14, NCP 18, SDG 6, SDG 12, SDG 13, SDG 14, SDG 15, & SDG 17*)
SDG 5 Gender equity[a]	**Agroforestry, integrated water management, disaster risk management** *Medium positive impact on this SDG but comes with potential trade-offs:* **management of supply chains** (*TO with SDG 6 and SDG7*), **enhanced urban food systems** (*TO with NCP 6, NCP 7, & SDG 6*), **use of local seeds** (*TO with NCP 12, SDG 2, & SDG 17*)
SDG 6 Clean water and sanitation	**Integrated water management, increased soil organic carbon, reduced post-harvest losses** *High positive impact on this SDG but comes with potential trade-offs:* **restoration of wetlands** (NCP 12, SDG 1, SDG 2, SDG 3, & SDG 9), **restoration of peatlands** (NCP 11, NCP 12, NCP 13, SDG 1, SDG 2, SDG 7, & SDG 8), **dietary change** (*TO with SDG 1, SDG 7, & SDG 14*), **reduced food waste** (*TO with SDG 3, SDG 5, & SDG 7*), **management of urban sprawl** (*TO with SDG 8*)
SDG 7 Affordable and clean energy	*High positive impact on this SDG but comes with potential trade-offs:* **Bioenergy and BECCS** (*TO with NCP 1, NCP 2, NCP 6, NCP7, NCP 8, NCP 12–18, SDG 1, SDG 2, SDG 3, SDG 6, SDG 13, & SDG 15*)
SDG 8 Decent work and economic growth	**Reduced post-harvest losses, disaster risk management** *High positive impact on this SDG but comes with potential trade-offs:* **reduced food waste** (*TO with SDG 3 SDG 5, & SDG 7*), **enhanced urban food systems** (*TO with NCP 6, NCP 7, & SDG 6*)
SDG 9 Industry, innovation, and infrastructure	**Disaster risk management** *High positive impact on this SDG but comes with potential trade-offs:* **sustainable sourcing** (*TO with NCP 12, NCP 17, SDG 2, & SDG 10*), **management of urban sprawl** (*TO with SDG 8*)
SDG 10 Reduced inequality	*High positive impact on this SDG but comes with potential trade-offs:* **Dietary change** (*TO with SDG 1, SDG 7, & SDG 14*), **management of urban sprawl** (*TO with SDG 8*)
SDG 11 Sustainable cities and communities	**Disaster risk management** *High positive impact on this SDG but comes with trade-offs:* **enhanced urban food systems** (*TO with NCP 6, NCP 7,, & SDG 6*), **management of urban sprawl** (*TO with SDG 8*)
SDG 12 Responsible production and consumption	*High positive impact on this SDG but comes with potential trade-offs:* **Dietary change** (*TO with SDG 1, SDG 7, & SDG 14*), **sustainable sourcing** (*TO with NCP 12, NCP 17, SDG 2, & SDG 10*), **management of supply chains** (*TO with SDG 6 & SDG 7*), **enhanced urban food systems** (*TO with NCP 6, NCP 7, & SDG 6*)
SDG 13 Climate action (includes benefits for both mitigation and adaptation)	**Agroforestry, integrated water management, increased soil carbon content, reduced soil erosion, reduced soil salinization, reduced soil compaction, fire management, reduced post-harvest losses, disaster risk management** *High positive impact on this SDG but comes with potential trade-offs:* **Increased food productivity** (*TO with NCP2, NCP 6, NCP7, NCP8, NCP 10, & SDG 14*), **agricultural diversification** *(TO with SDG 10)*, **improved and sustainable forest management** (*TO with NCP 9, NCP 10, NCP 12, SDG 1, & SDG 2*), **reduced deforestation** (*TO with NCP 11, NCP 12, NCP 17, SDG 1, SDG 2, SDG 7, SDG 8, SDG 9, SDG 10, & SDG 17*), **reforestation/restoration** (*TO with NCP 6, NCP 9, NCP 10, NCP 12, SDG 1, SDG 2, SDG 5, SDG 6, & SDG 10*), **afforestation** (*TO with NCP 1, NCP 2, NCP 6, NCP 7, NCP 8, NCP 9, NCP 10, NCP 12, NCP 13, NCP 18, SDG 1, SDG 2, SDG 5, SDG 6, & SDG 10*), **biochar** (*TO with NCP 1, NCP 3, NCP 12, SDG 1, SDG 2, SDG 3, SDG 15*), **restoration of wetlands** (*TO with NCP 12, SDG 1, SDG 2, SDG 3, & SDG 9*), **biodiversity conservation** (*TO with NCP 12, NCP 13, SDG 1, SDG 2, SDG 5, SDG 7, SDG 8, SDG 9, & SDG 16*), **management of urban sprawl** (*TO with SDG 8*)

(Continues)

TABLE 12 (Continued)

SDGs	Response options with large positive impacts for this goal [and potential trade-offs (TO)]
SDG 14 Life below water	*High positive impact on this SDG but comes with potential trade-offs:* **restoration of wetlands** (*TO with NCP 12, SDG 1, SDG 2, SDG 3, & SDG 9*), **biodiversity conservation** (*TO with NCP 12, NCP 13, SDG 1, SDG 2, SDG 5, SDG 7, SDG 8, SDG 9, SDG 16*)
SDG 15 Life on land	**Improved cropland management, improved grazing management, agroforestry, integrated water management, increased soil carbon, fire management** *High positive impact on this SDG but comes with potential trade-offs:* **avoided grassland conversion** (*TO with NCP 12, SDG 1, SDG 2, & SDG 8*), **improved and sustainable forest management** (*TO with NCP 9, NCP 10, NCP 12, SDG 1, & SDG 2*), **reduced deforestation** (*TO with NCP 11, NCP 12, NCP 17, SDG 1, SDG 2, SDG 7, SDG 8, SDG 9, SDG 10, & SDG 17*), **reforestation/restoration** (*TO with NCP 6, NCP 9, NCP 10, NCP 12, SDG 1, SDG 2, SDG 5, SDG 6, & SDG 10*), **restoration of wetlands** (*TO with NCP 12, SDG 1, SDG 2, SDG 3, & SDG 9*), **restoration of peatlands** (*TO with NCP 12, SDG 1, SDG 2, SDG 7, & SDG 8*), **biodiversity conservation** (*TO with NCP 12, NCP 13, SDG 1, SDG 2, SDG 5, SDG 7, SDG 8, SDG 9, & SDG 16*), **management of urban sprawl** (*TO with SDG 8*)
SDG 16 Peace and justice and strong institutions	**Disaster risk management** *High positive impact on this SDG but comes with potential trade-offs:* **enhanced urban food systems** (*TO with NCP 6, NCP 7, & SDG 6*), **use of local seeds** (*TO with NCP 12, SDG 2, & SDG 17*)
SDG 17 Partnerships to achieve the goals	None

[a]Only moderate co-benefits were seen in these categories.

4.1 | Identifying co-benefits for people and nature

There are a clear range of potential synergies through co-benefits provided by the assessed response options. For example, there are positive co-benefits between many response options and important SDGs: these include positive poverty reduction impacts (SDG 1) from activities like integrated water management and increased soil carbon, and strengthened good health (SDG 3) from reducing pollution, fire management, and disaster risk management approaches. In some cases, our review has identified some response options that might not have been obvious choices for improvements in SDGs or NCPs at first glance, such as the important role that integrated water management could potentially play for gender equity. By starting our review with response options and actions first, and then comparing them across SDGs and NCPs for co-benefits, some of these interesting and unexpected interactions emerged. However, as many studies have noted, achieving co-benefits requires explicit assessments and agreements on criteria, and an understanding that not all co-benefits can accrue in every context (Hultman, Lou, & Hutton, 2020).

Table 12 indicates the strongest options identified from the assessment for specific SDGs (i.e., those for which Tables 3–8 indicated large positive impacts). However, while this can provide a suggestive template for what the preferred response options for each priority SDG might be, policymakers also need to consider the specific trade-offs that may result, which are indicated in parentheses (indicating where negative impacts were found in the literature reviews).

For NCPs, examples of positive co-benefits include positive ecosystem impacts on habitat maintenance from activities like reduced land conversion across forests, grasslands, wetlands, and peatlands and fire management. Table 13 indicates the strongest options that emerged from the assessment of response options for specific NCPs, again providing the caveat that some of these options come with more trade-offs than others. As the recent IPBES Global Assessment noted, many NCPs can trade-off with one another, and achieving synthesis across multiple NCPs is an important policy goal (IPBES, 2019).

4.2 | Highlighting interactions between SDGs and NCPs

The strong synergies *between* positive co-benefits on both NCPs and SDGs for a number of response options (Table 11) are an important finding. This indicates that there are potentially win–wins that do not require the degradation of natural capital and ecosystems to achieve poverty and development objectives (Miteva, 2019). For example, pollination services (NCP 2) are essential for crop production necessary to reduce hunger (SDG 2; Dangles & Casas, 2019). While the literature remains rather thin on many of these interactions, evidence is growing that mutual reinforcement between improved environment management and goals for human well-being is in fact achievable (Schleicher, Schaafsma, & Vira, 2018).

Response options in which there are positive interactions and synergies across both NCPs and SDGs can help deliver on a range of social and ecological benefits. One of these win–win options, agroforestry, is noted in Figure 1. Agroforestry involves the deliberate planting of trees in croplands and silvopastoral systems and is a particularly integrative practice in that it is usually carried out to bring both ecological and social benefits, ranging from improved soil health to increased farm income. The literature reviews noted that agroforestry can contribute to poverty reduction (Leakey & Simons, 1997), reduces food insecurity (Mbow et al., 2014), and positively contributes to more nutritious diets (Haddad, 2000), as well as mimics natural ecosystem diversity (Jose, 2009), provides habitat for pollinators (Dainese et al., 2019), and increases soil water infiltration capacity

TABLE 13 Highlighting response options for individual Nature's Contributions to People (NCPs)

NCPs	Response options with large positive impacts for this contribution [and potential trade-offs (TO)]
NCP 1 Habitat creation and maintenance	**Agroforestry, integrated water management** *High positive impact on this NCP but comes with potential trade-offs:* **improved and sustainable forest management** (*TO with NCP 9, NCP 10, NCP 12, SDG 1, & SDG 2*), **reduced deforestation** (*TO with NCP 11, NCP 12, NCP 17, SDG 1, SDG 2, SDG 7, SDG 8, SDG 9, SDG 10, & SDG 17*), **reforestation/restoration** (*TO with NCP 6, NCP 9, NCP 10, NCP 12, SDG 1, SDG 2, SDG 5, SDG 6, & SDG 10*), **restoration of wetlands** (*TO with NCP 12, SDG 1, SDG 2, SDG 3, & SDG 9*), **restoration of peatlands** (NCP 12, SDG 1, SDG 2, SDG 7, SDG 8), **biodiversity conservation** (*TO with NCP 12, NCP 13, SDG 1, SDG 2, SDG 5, SDG 7, SDG 8, SDG 9, & SDG 16*)
NCP 2 Pollination and dispersal of seeds and other propagules	*High positive impact on this NCP but comes with potential trade-offs:* **biodiversity conservation** (*TO with NCP 12, NCP 13, SDG 1, SDG 2, SDG 5, SDG 7, SDG 8, SDG 9, & SDG 16*)
NCP 3 Regulation of air quality	**Reduced soil erosion** *High positive impact on this NCP but comes with potential trade-offs:* **management of urban sprawl** (*TO with SDG 8*)
NCP 4 Regulation of climate	**Agroforestry, increased soil carbon, fire management, reduced post-harvest losses** *High positive impact on this NCP but comes with potential trade-offs:* **Increased food productivity** (*TO with NCP2, NCP 6, NCP7, NCP8, NCP 10, & SDG 14*), **reduced deforestation** (*TO with NCP 11, NCP 12, NCP 17, SDG 1, SDG 2, SDG 7, SDG 8, SDG 9, SDG 10, & SDG 17*), **reforestation** (*TO with NCP 6, NCP 9, NCP 10, NCP 12, SDG 1, SDG 2, SDG 5, SDG 6, SDG 10*), **afforestation** (*TO with NCP 1, NCP 2, NCP 6, NCP 7, NCP 8, NCP 9, NCP 10, NCP 12, NCP 13, NCP 18, SDG 1, SDG 2, SDG 5, SDG 6, & SDG 10*), **biochar** (*TO with NCP 1, NCP 3, NCP 12, SDG 1, SDG 2, SDG 3, SDG 15*), **restoration of wetlands** (*TO with NCP 12, SDG 1, SDG 2, SDG 3, & SDG 9*), **mineral weathering** (TO with NCP 7 & SDG 6), **bioenergy and BECCS** (*TO with NCP 1, NCP 2, NCP 6, NCP7, NCP 8, NCP 12–18, SDG 1, SDG 2, SDG 3, SDG 6, SDG 13, & SDG 15*), **dietary change** (*TO with SDG 1, SDG 7 & SDG 14*), **reduced food waste** (*TO with SDG 3, SDG 5, & SDG 7*)
NCP 5 Regulation of ocean acidification (*note: any action with high mitigation potential on NCP 4 is assumed to have same positive impact on ocean acidification*)	**Agroforestry, increased soil carbon, fire management, reduced post-harvest losses** *High positive impact on this NCP but comes with potential trade-offs:* **Increased food productivity** (*TO with NCP2, NCP 6, NCP7, NCP8, NCP 10, & SDG 14*), **reduced deforestation** (*TO with NCP 11, NCP 12, NCP 17, SDG 1, SDG 2, SDG 7, SDG 8, SDG 9, SDG 10, & SDG 17*), **reforestation** (*TO with NCP 6, NCP 9, NCP 10, NCP 12, SDG 1, SDG 2, SDG 5, SDG 6, SDG 10*), **afforestation** (*TO with NCP 1, NCP 2, NCP 6, NCP 7, NCP 8, NCP 9, NCP 10, NCP 12, NCP 13, NCP 18, SDG 1, SDG 2, SDG 5, SDG 6, & SDG 10*), **biochar** (*TO with NCP 1, NCP 3, NCP 12, SDG 1, SDG 2, SDG 3, SDG 15*), **restoration of wetlands** (*TO with NCP 12, SDG 1, SDG 2, SDG 3, & SDG 9*), **mineral weathering** (TO with NCP 7 & SDG 6), **bioenergy and BECCS** (*TO with NCP 1, NCP 2, NCP 6, NCP7, NCP 8, NCP 12–18, SDG 1, SDG 2, SDG 3, SDG 6, SDG 13, & SDG 15*), **dietary change** (*TO with SDG 1, SDG 7, & SDG 14*), **reduced food waste** (*TO with SDG 3, SDG 5, & SDG 7*)
NCP 6 Regulation of freshwater quantity, flow, and timing	**Integrated water management, increased soil carbon, reduced soil compaction** *High positive impact on this NCP but comes with potential trade-offs:* **improved and sustainable forest management** (*TO with NCP 9, NCP 10, NCP 12, SDG 1, & SDG 2*), **reduced deforestation** (*TO with NCP 11, NCP 12, NCP 17, SDG 1, SDG 2, SDG 7, SDG 8, SDG 9, SDG 10, & SDG 17*), **restoration of wetlands** (*TO with NCP 12, SDG 1, SDG 2, SDG 3, & SDG 9*), **restoration of peatlands** (*TO with NCP 12, SDG 1, SDG 2, SDG 7, & SDG 8*), **management of urban sprawl** (*TO with SDG 8*)
NCP 7 Regulation of freshwater and coastal water quality	**Integrated water management, increased soil carbon, reduced soil salinization, reduced compaction, reduced pollution** *High positive impact on this NCP but comes with potential trade-offs:* **Improved and sustainable forest management** (*TO with NCP 9, NCP 10, NCP 12, SDG 1, SDG 2*), **reduced deforestation** (*TO with NCP 11, NCP 12, NCP 17, SDG 1, SDG 2, SDG 7, SDG 8, SDG 9, SDG 10, & SDG 17*), **restoration of wetlands (** *TO with NCP 12, SDG 1, SDG 2, SDG 3, & SDG 9*), **restoration of peatlands** (*TO with NCP 12, SDG 1, SDG 2, SDG 7, & SDG 8*), **management of urban sprawl** (*TO with SDG 8*)
NCP 8 Formation, protection, and decontamination of soils and sediments	**Agroforestry, increased soil carbon, reduced soil erosion, reduced salinization, reduced compaction** *High positive impact on this NCP but comes with potential trade-offs:* **Improved and sustainable forest management** (*TO with NCP 9, NCP 10, NCP 12, SDG 1, SDG 2*), **biochar** (*TO with NCP 1, NCP 3, NCP 12, SDG 1, SDG 2, SDG 3, SDG 15*), **restoration of wetlands (** *TO with NCP 12, SDG 1, SDG 2, SDG 3, & SDG 9*), **restoration of peatlands** (*TO with NCP 12, SDG 1, SDG 2, SDG 7, & SDG 8*), **biodiversity conservation** (*TO with NCP 12, NCP 13, SDG 1, SDG 2, SDG 5, SDG 7, SDG 8, SDG 9, & SDG 16*), **management of urban sprawl** (*TO with SDG 8*)
NCP 9 Regulation of hazards and extreme events	**Fire management, reduced landslides, disaster risk management** *High positive impact on this NCP but comes with potential trade-offs:* **restoration of wetlands** (*TO with NCP 12, SDG 1, SDG 2, SDG 3, & SDG 9*)
NCP 10 Regulation of organisms detrimental to humans	**Agroforestry, increased soil carbon** *High positive impact on this NCP but comes with potential trade-offs:* **agricultural diversification** *(TO with SDG 10)*, **use of local seeds** (*TO with NCP 12, SDG 2 & SDG 17*)
NCP 11 Energy	*High positive impact on this NCP but comes with potential trade-offs:* **bioenergy and BECCS** (*TO with NCP 1, NCP 2, NCP 6, NCP7, NCP 8, NCP 12–18, SDG 1, SDG 2, SDG 3, SDG 6, SDG 13 & SDG 15*)

(Continues)

TABLE 13 (Continued)

NCPs	Response options with large positive impacts for this contribution [and potential trade-offs (TO)]
NCP 12 Food and feed	**Improved cropland management, improved grazing land management, improved livestock management, agroforestry, integrated water management, increased soil carbon, reduced post-harvest losses** *High positive impact on this NCP but comes with potential trade-offs:* **Increased food productivity** (*TO with NCP2, NCP 6, NCP7, NCP8, NCP 10, & SDG 14*) **agricultural diversification** (*TO with SDG 10*), **dietary change** (*TO with SDG 1, SDG 7, & SDG 14*), **reduced food waste** (*TO with SDG 3, SDG 5, & SDG 7*), **enhanced urban food systems** (*TO with NCP 6, NCP 7, & SDG 6*), **risk sharing instruments** (*TO with NCP 1, NCP 2, NCP 4, NCP 7, NCP 8, NCP 10, NCP 14, NCP 18, SDG 6, SDG 12, SDG 13, SDG 14, SDG 15, & SDG 17*)
NCP 13 Materials and assistance	*High positive impact on this NCP but comes with potential trade-offs:* **Material substitution** (*TO with NCP1, SDG 2, SDG 9, & SDG 15*)
NCP 14 Medicinal, biochemical, and genetic resources	*High positive impact on this NCP but comes with potential trade-offs:* **biodiversity conservation** (*TO with NCP 12, NCP 13, SDG 1, SDG 2, SDG 5, SDG 7, SDG 8, SDG 9, & SDG 16*)
NCP 15 Learning and inspiration	*High positive impact on this NCP but comes with potential trade-offs*: **biodiversity conservation** (*TO with NCP 12, NCP 13, SDG 1, SDG 2, SDG 5, SDG 7, SDG 8, SDG 9, & SDG 16*), **use of local seeds** (*TO with NCP 12, SDG 2, & SDG 17*)
NCP 16 Physical and psychological experiences	*High positive impact on this NCP but comes with potential trade-offs:* **biodiversity conservation** (*TO with NCP 12, NCP 13, SDG 1, SDG 2, SDG 5, SDG 7, SDG 8, SDG 9, & SDG 16*)
NCP 17 Supporting identities	*High positive impact on this NCP but comes with potential trade-offs:* **biodiversity conservation** (*TO with NCP 12, NCP 13, SDG 1, SDG 2, SDG 5, SDG 7, SDG 8, SDG 9, & SDG 16*), **use of local seeds** (*TO with NCP 12, SDG 2, & SDG 17*)
NCP 18 Maintenance of options	*High positive impact on this NCP but comes with potential trade-offs:* **biodiversity conservation** (*TO with NCP 12, NCP 13, SDG 1, SDG 2, SDG 5, SDG 7, SDG 8, SDG 9, & SDG 16*), **use of local seeds** (*TO with NCP 12, SDG 2, & SDG 17*)

(Ilstedt, Malmer, Verbeeten, & Murdiyarso, 2007), among other benefits. As a result, our assessment of this practice shows a range of positive benefits for both NCPs and SDGs: for climate across three NCPs and one SDG (Climate action); benefits for biodiversity across four NCPs and one SDG (Life on Land); and benefits for humans across one NCP (Supporting identities) and five SDGs (Figure 1).

However, not all options are as integrative or beneficial as agroforestry. For other response options, there are trade-offs between SDGs and NCPs. For example, some response options stand out as being particularly positive across a range of SDGs, but few NCPs: *management of supply chains*, *improved food processing and retail*, and *disaster risk management*. Conversely, some options deliver co-benefits for many NCPs but few SDGs: *reduced deforestation and degradation*, *restoration and avoided conversion of coastal wetlands*, *and restoration and avoided conversion of peatlands*. These response options are primarily focused on natural land management options that minimize human impacts and maximize ecosystem functions, while the SDG-focused options are ones that improve access to food and reduce risks to livelihoods, with little attention to benefits for ecosystems.

There are also options that deliver a balanced set of co-benefits across both SDGs and NCPs with minimal side effects; these include *improved cropland management*, *improved grazing land management*, *improved livestock management*, *agroforestry*, *nearly all soil management options aside from biochar*, *fire management*, *reduced landslides*, *reduced pollution*, and *reduced post-harvest losses*. These particular options focus on human-dominated systems and seek to improve these in ways that have positive outcomes for both social and ecological components, while also minimizing external risks or improving resilience. Such approaches that recognize socio-ecological complexity in an integrated manner are increasingly important in ecosystem governance (Vasseur et al., 2017), as are evidenced in rising attention to concepts like "nature-based solutions" and "ecosystem-based adaptation" (Seddon et al., 2019, 2020).

4.3 | Making better policy choices to achieve global goals

The Paris Agreement and SDGs both reflect global goals for human and environmental well-being, but there are also potentially serious trade-offs between both of them and with other global objectives, like biodiversity conservation (Iyer et al., 2018; Sachs et al., 2019; von Stechow et al., 2015). There is also concern that we are failing to make progress on many of the SDGs and on Paris Agreement pledges (ECOSOC, 2019). It is possible that one reason for slow progress is conflict among and between different goals, and hence, a closer look at response options could help identify areas where conflicts and trade-offs will need to be managed.

Our analysis can also help focus attention on beneficial options that could be included in Nationally Determined Contributions (NDCs) for the Paris Agreement, where countries note their pledges for mitigation and adaptation and how they intend to meet these goals (Iyer et al., 2018). Recent analysis of these NDCs for their use of "nature-based solutions" reveals that 77% of NDCs contain at least one quantitative target for ecosystems in general (Seddon et al., 2019), but many NDCs are not specific on what response options might be included to meet that target. Among land-based actions, the forest sector generally receives the most attention in NDCs, as it can make significant contributions to both mitigation and

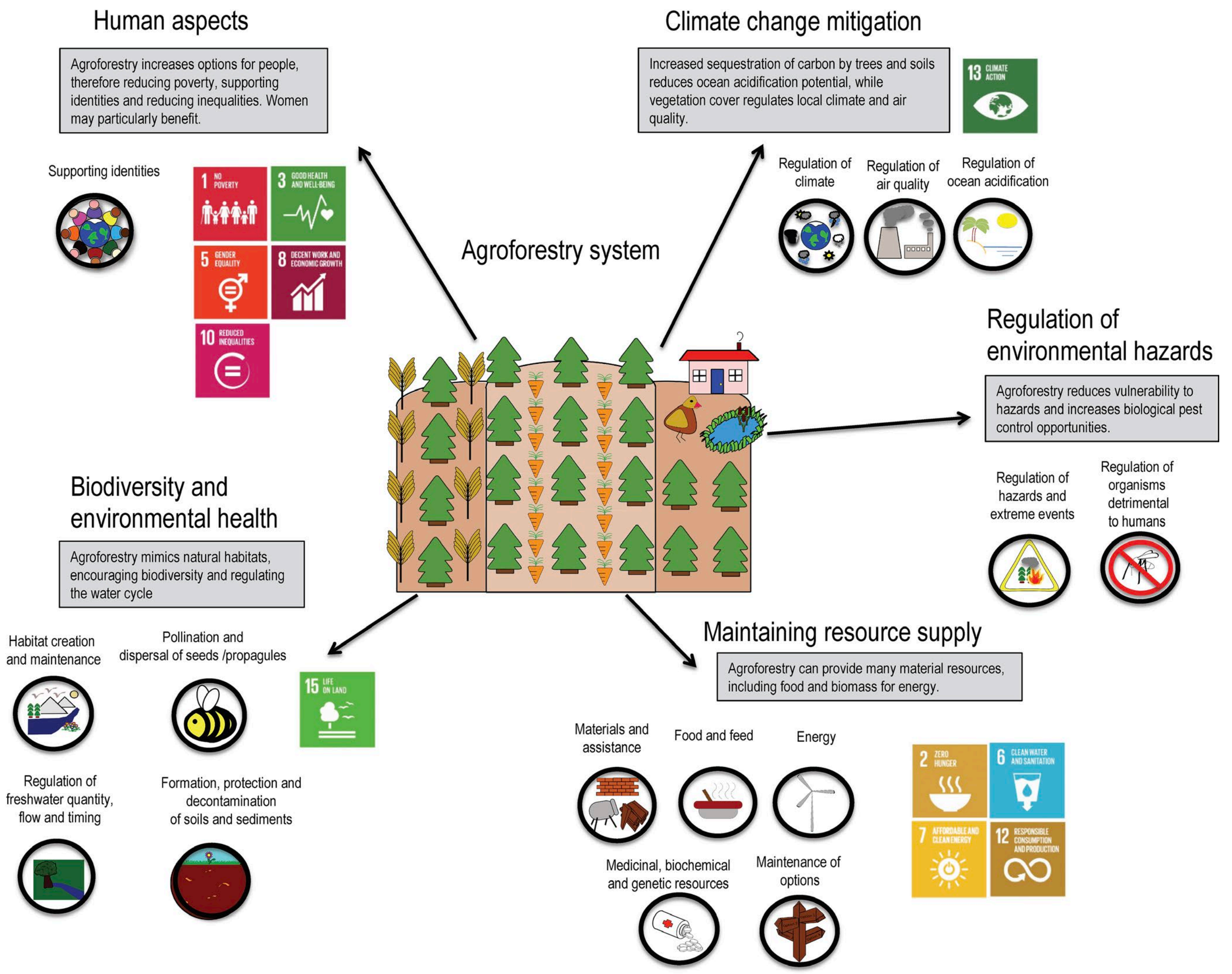

FIGURE 1 Impacts on Nature's Contributions to People (NCPs) and Sustainable Development Goals (SDGs) within Agroforestry Systems. Note: Circles are key NCPs and squares are key SDGs

adaptation goals; however, as we note, most options around forests do come with potential trade-offs related to food production and other NCPs that need to be recognized.

Moreover, the analysis presented here and in Smith et al. (2020) notes that significant mitigation benefits with minimal adverse side effects can also be achieved through attention to better agricultural and food practices (e.g., increased food productivity or increased soil organic carbon). However, there is very little attention in NDCs to these measures, or to demand-side shifts (e.g., reduced post-harvest losses or dietary change; Roe et al., 2019), which also shows promise in the analysis here. Thus, encouraging future NDC submissions to be explicit about what policies, options, and pathways will be used to achieve overall mitigation and adaptation goals could draw on methodological analysis such as that presented here. That is, the use of a trade-off and co-benefit literature review, drawing on multiple case studies, can clarify for policymakers the particular response options that best match their social and environmental goals within a specific geographical and societal context, and which minimize the most serious trade-offs.

Another key point emerging from this analysis is the need for policy coherence to support implementation of the response options, since there are many interactions and potential co-benefits that can be realized from bringing different response options and goals together (Griggs et al., 2014). Increasingly policymakers and researchers are thinking about "nexus" approaches that encourage integrated planning across sectors, particularly synergies between environmental and social planning (Weitz, Nilsson, & Davis, 2014). The goal of nexus approaches is "improving resource use efficiency and avoiding adverse impacts of single-sector development strategies" (Ringler & Lawford, 2013, 618). Our analysis here supports seeking opportunities for nexus outcomes, where multiple response options could co-deliver across a mix of NCPs and SDGs (e.g., water–land–energy–food), while also delivering climate mitigation and adaptation benefits (Karabulut, Udias, & Vigiak, 2019). These integrated and nexus approaches to provide co-benefits and synergies will require frequent assessment and strong engagement of stakeholders, given the complexity of challenges (Raymond et al., 2017; Reed et al., 2019).

4.4 | Study limitations, gaps, and future research

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 trends qualitatively, without the possibility of detailed quantification (e.g., how a doubling of area devoted to one response option would affect an NCP or SDG). Furthermore, because many of the NCPs and SDGs trade-off with one another (e.g., NCP 1 vs. NCP 11, or NCP 6 vs. SDG 7), simple assessments cannot fully capture the range of all interactions.

The context for any given option also needs to be considered carefully. For example, there are physical spatial limits on where many response options can be applied, for which this analysis was unable to go into contextual detail. Additionally, trying to assess the literature across the global scale has meant that many important, context-specific interactions (e.g., by location, ecosystem type, or administrative unit) cannot be accounted for. This is complicated by the fact that the literature is skewed toward some regions more than others, depending on the option assessed (e.g., Kuyah et al., 2016). Future assessments could help to clarify where these spatial biases are most relevant for which practices and options.

Furthermore, all land-based options we assessed are scale dependent, and the potential adverse side effects of practices such as BECCS are reflective of large-scale implementation. 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 (Cacho, Negri, Zumpf, & Campbell, 2018), arguing further for multiscalar, nexus approaches to policy implementation.

As Tables 3–8 demonstrate, there are also considerable knowledge gaps. Many response options have not been investigated for their impacts on SDGs or NCPs, and thus, our literature reviews turned up no data. There are many suggestive relationships that would benefit from further research; for example, 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. For example, we do have studies that show how gender impacts farming (i.e., women and men engage in different practices), but we are less clear on the reverse: that is, how do different farming practices result in more or less gender equity (the specific SDG goal). Thus, the directionality of impacts between options and SDGs/NCPs was particularly challenging in reviewing the literature. Furthermore, 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., there is considerably less information on pollination services, air quality, or hazard regulation impacts linked to different specific land use practices).

5 | CONCLUSIONS

The world faces a series of interlinked challenges in our land sector: the need for mitigation of greenhouse gases, adaptation to existing and impending climate change, reducing land degradation, and ensuring food security. How to potentially address all the challenges in an integrated manner, without undue impacts on any of these challenges or on socio-environmental systems, is the goal of many countries in their NDCs, adoption of SDGs, and other national policies. Identifying potential options was also the overall goal for many countries in calling for the IPCC Climate Change and Land report.

Our comprehensive assessment concludes that a number of response options can make a valuable contribution to tackling these land challenges and at the same time help in eradicating poverty, provisioning and regulating water, producing food, energy, and other materials, and supporting sustainable cities and communities, among other positive benefits associated with NCPs and SDGs. The fact that there are a wide range of policy responses that have the potential to make positive contributions to sustainable development, ecosystem services, and other societal goals, with minimal trade-offs, is good news.

However, as our results suggest, care must be taken to acknowledge and manage the potential trade-offs where they do exist. Our analysis has pointed out that some response options with high mitigation or adaptation benefits do show potentially large adverse impacts on some SDGs or NCPs. Land management-based options that require significant land use change can adversely affect efforts to eradicate poverty and eliminate hunger (Molotoks et al., 2018); such trade-offs were identified with afforestation and BECCS/bioenergy in particular. Recognizing these trade-offs in advance can help policymakers find alternative measures, or at least possibilities to avoid or minimize negative effects, through well-managed implementation, safety nets, and welfare policies, among other solutions (Trisos et al., 2019). Similarly, social development options that are focused on human improvement to the exclusion of natural systems can have adverse effects on NCPs. Policymakers face strong challenges in trying to balance these competing goals, and use of trade-off analyses derived from extensive literature reviews, as we have done here, is one way to help identify these pitfalls.

Furthermore, our analysis also has highlighted the many important synergies between SDG goals and NCP supply. Some options to tackle land and climate challenges do in fact provide a balanced set of co-benefits across both SDGs and NCPs. What these balanced options have in common is that they acknowledge the integration of socio-ecological systems, rather than having primary objectives that are predominantly environmental or social. However, many of the positive co-benefits that are possible will not happen automatically, and are dependent on institutional and enabling conditions for success (IPCC, 2019). All too often, land and climate policies are not planned in an integrated manner, as examination of many existing NDCs reveals, and when synergies are not managed for explicitly, this can result in lost opportunities. Nexus approaches to socio-environmental systems and "nature-based solutions" that have an explicitly integrated human/ecosystem benefit model are two approaches identified here that show promise.

Thus, how response options and policies are designed and delivered will play an important role in determining how beneficial they are in supporting SDG and NCP goals, and future research on the implementation successes and failures of these options is sorely needed (Independent Group of Scientists appointed by the Secretary-General, 2019). Ensuring that policymakers can anticipate adverse impacts and positive co-benefits 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 co-benefit and trade-off interactions in the overall literature.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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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

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 decontam-ination 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	Support-ing identities	Maintenance of options
Agriculture	**Increased food productivity**	Higher productivity spares land (e.g. Balmford et al. 2018) especially if intensification is done sustainably; conventional intensification associated with biodiversity and habitat loss (Beckmann et al. 2019)	May reduce native pollinators if reliant on increased chemical inputs (Potts et al., 2010) but evidence is mixed on sustainable intensification	N/A	Could provide significant mitigation potential (Smith et al. 2020) by avoiding emissions that would occur if increased food demand were met through expansion of the agricultural land area (Bustamante et al., 2014; Lamb et al., 2016)	Mitigation potential will reduce ocean acidification	Food productivity increases likely will increase demand for irrigation, which affects water flow and timing (Mueller et al., 2012; Rockström et al., 2009).	Food productivity increases could impact water quality if increases in chemicals used, but evidence is mixed on sustainable intensification (Mueller et al., 2012; Rockström et al., 2009)	Context dependent: Intensification through additional input of nitrogen fertiliser can result in negative impacts on climate, soil, water and air pollution (Tilman, Cassman, Matson, Naylor, & Polasky, 2002), but sustainable intensification can make positive use of soil ecosystem services (Schulte et al., 2014)	N/A	Increasing food production through agro-chemicals may increase pest resistance over time (Tilman et al., 2002), but sustainable intensification tries to avoid this.	N/A	Sustainable intensification has strong potential to close yield gaps (Tilman, Balzer, Hill, & Befort, 2011).	N/A	N/A	N/A	N/A	Food production has cultural components that can benefit social identities (Tengberg et al., 2012)	N/A
	Improved cropland management	Improved cropland management can contribute to diverse agroecosystems (Tscharntke, Klein, Kruess, Steffan-Dewenter, & Thies, 2005) and promotes soil biodiversity (Oehl, Laczko, Oberholzer, Jansa, & Egli, 2017)	Better crop management can contribute to maintaining native pollinators (Dainese et al., 2019; Gardiner et al., 2009)	Some potential benefits from some practices (e.g. residue retention instead of burning would reduce air pollution, Huang et al. 2012) but little literature on other practices	Could provide moderate levels of mitigation (1.4-2.3 $GtCO_2e\ yr^{-1}$ (Smith et al., 2014, 2008)	Mitigation potential will reduce ocean acidification	Cropland conversion leads to poorer water quantity due to runoff (Scanlon, Jolly, Sophocleous, & Zhang, 2007), improved management can reduce this (Fawcett, Christensen, & Tierney, 1994).	Cropland conversion has major impacts on water quantity (Scanlon et al., 2007). Cropland management practices such as conservation tillage improve downstream water quality	Improved cropland management has strong positive impacts on soils (Paustian et al., 2016)	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 (Dar & Laxmipathi Gowda, 2013; Godfray & Garnett, 2014; Rosegrant & Cline, 2003)	N/A	N/A	N/A	N/A	Many cropping systems have cultural components that can benefit social identities (Tengberg et al., 2012)	N/A

	Improved grazing land manage-ment	Can contribute to improved habitat for other species (Pons, Lambert, Rigolot, & Prodon, 2003; Plantureux, Peeters, & McCracken, 2005)	Possible that it may increase native pollinators but unclear evidence	N/A	Moderate mitigation potential (1.4–1.8 $GtCO_2$ yr^{-1}) (P. Smith et al., 2008)	Mitigation potential will reduce ocean acidification	Best practices can improve water flow (Hibbert, 1983)	Best practices can improve water quality (Hibbert, 1983)	Improved grassland management increases soil carbon and quality (Conant & Paustian, 2002; Paustian et al., 2016)	N/A	N/A	N/A	Improved grassland management has large potential contribute to food security through better livestock production (O'Mara, 2012)	Grassland management can provide other materials (e.g. biofuel materials) (Prochnow, Heiermann, Plöchl, Amon, & Hobbs, 2009)	N/A	N/A	N/A	Many pastoralists have close cultural connections to livestock (Ainslie, 2013)	N/A
	Improved livestock manage-ment	Can contribute to improved habitat if more efficient animals used, leading to less feed required (Strassburg et al., 2014)	N/A	N/A	Moderate mitigation potential from direct and indirect pathways (0.2–1.8 $GtCO_2e$ yr^{-1} (P. Smith et al., 2008;Herrero et al., 2016)	Mitigation potential will reduce ocean acidification.	N/A	Improved industrial livestock production can reduce water contamination (e.g. reduced effluents) (Hooda, Edwards, Anderson, & Miller, 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 (Hooft, Wollen, & Bhandari, 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 strongly improve or provide additional habitat, including as conservation corridors (Jose, 2009; Jose 2012; Bhagwat, Willis, Birks, & Whittaker, 2008)	Diverse agroforestry systems can be beneficial for pollinators (Dainese et al., 2019; Klein, Steffan-Dewenter, Buchori, & Tscharntke, 2002)	Trees in the landscape can remove air pollutants (Sutton et al., 2007)	Currently conserve carbon stocks equivalent to 0.7 $GtCO_2$ yr^{-1}; global potential to increase range from 0.1 to 5.7 $GtCO_2$ yr^{-1} (Hawken, 2017); local climate benefits as well	Mitigation potential will reduce ocean acidification.	Planting trees on farms can increase soil water infiltration capacity (Ilstedt, Malmer, Verbeeten, & Murdiyarso, 2007) and water quantity (Jose 2009)	Agro-forestry can be used to increase ecosystem services benefits, such as water quality, depending on species used (Jose 2009)	Mixed plantings improve soil (Mbow, Smith, Skole, Duguma, & Bustamante, 2014; Rao, Nair, & Ong, 1997)	Agroforestry can reduce vulnerability to hazards like wind and drought (Thorlakson & Neufeldt, 2012)	Diversity generally improves opportunities for biological pest control through beneficial arthropods (Gardiner et al., 2009; Rao, Singh, & Day, 2000); can reduces pests/pathogens on smallholder farms (Vignola et al., 2015)	Agroforestry can be used to produce biomass for energy (Mbow, Smith, et al., 2014)	Agroforestry contributes to food productivity and reduces food insecurity (Mbow, Van Noordwijk, et al., 2014)	Produces timber, firewood and animal fodder (Mbow, Smith, et al., 2014)	Can provide medicinal and other resources (Rao, Palada, & Becker, 2014)	N/A	N/A	Many agroforestry systems have important 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	Diversification can enhance pollinator diversity, depending	N/A	Globally unquantified potential for mitigation	N/A	Changing crops may improve water infiltration capacity but depends	Changing crops may improve water quality if less pesticides are used, but	Diversification can introduce some crops that may have positive soil	N/A	Diverse agroecosystems tend to have less detrimental impacts due	N/A	Diversification is associated with increased access to	Diversification could provide additional materials and farm benefits	Practices for agricultural diversification can include medicinal plants in farm	N/A	N/A	Many diverse cropping systems have cultural	Can contribute to maintaining biodiversity through native plantings (Sardiñas &

		diversity to mimic more natural systems including functional biodiversity at multiple spatial and/or temporal scales (Kremen, Iles, & Bacon, 2012; Lin, 2011)	on crops used (Altieri & Letourneau, 1982; Dainese et al., 2019; Sardiñas & Kremen, 2015)				highly on context, not function of diversification alone, so unclear effects	depends highly on context, not function of diversification alone, so unclear effects	qualities (eg nitrogen fixation) and crop rotation with multiple crops can improve soil carbon (McDaniel, Tiemann, & Grandy, 2014)		to in-field habitat for natural pest defences (Altieri & Letourneau, 1982; Gardiner et al., 2009)		income and additional food sources for the farming household (Ebert, 2014; J. N. Pretty, Morison, & Hine, 2003)	(Van Huylenbroeck, Vandermeulen, Mettepenningen, & Verspecht, 2007)	systems (Chauhan, 2010)			components (Rao et al., 2014)	Kremen, 2015)
	Avoidance of conversion of grassland to cropland	Is aimed at preserving natural grassland habitat (Peeters, 2009)	N/A	N/A	Mitigation potential of 0.03 Gt CO_2 yr^{-1} (P. Smith et al., 2019)	Mitigation potential will reduce ocean acidification.	Will likely improve water flow (inferred from improved soil quality) (Saviozzi, Levi-Minzi, Cardelli, & Riffaldi, 2001)	Will likely improve water quality (inferred from improved soil quality) (Saviozzi et al., 2001)	Strongly improves soil quality (Saviozzi et al., 2001)	N/A	Intact agroecosystems tend to have less detrimental impacts from pests but little literature specifically on grasslands	N/A	Reducing cropland conversion can reduce food production potentials (West et al., 2010)	N/A	N/A	N/A	N/A	N/A	Retaining natural ecosystems can preserve genetic diversity (Ekins, Simon, Deutsch, Folke, & De Groot, 2003)
	Integrated water management	Ecosystem health and services can be enhanced by improving water management (Bernex, 2016; Boelee, Chiramba, & Khaka, 2011; Jingya Liu et al., 2016; Lloyd et al., 2013)	Some IWM strategies generate synergies between multiple ecosystem services, such as pollination, yield and farm profitability (Hipólito, Boscolo, & Viana, 2018)	IWM practices exert strong influence on ecosystem structure and function, with potential implications for regulating air quality (Xia et al., 2017)	IWM influences the storage and flow of water in watersheds (Eisenbies, Aust, Burger, & Adams, 2007) which are important for regulating microclimates	N/A	IWM practices such as preventing aquifer and surface water depletion, Managed Aquifer Recharge (MAR), enhancing rainwater management and increasing water use in discharge areas can increase water quantity (Nejad, 2013; Pereira, Cordery, & Iacovides, 2002)	Improving regulations for water sharing, trading and pricing in IWM can increase water quality (ADB, 2016)	IWM can provide co-benefits such as healthier soils (D. Grey & Sadoff, 2007; Junguo Liu et al., 2017)	IWM like Underground Taming of Floods for Irrigation (UTFI),and reducing evaporation losses can reduced impacts of extreme weather events (Dillon & Arshad, 2016)	N/A	IWM could indirectly help production of biomass for energy and firewood by providing sufficient water but no specific literature	Water conservation and rational water allocations help meet increasing demand for food and feed (Ward & Pulido-Velazquez, 2008; WBCSD, 2014)	IWM indirectly supports forest growth conditions thereby providing wood and fodder and other materials but. no specific literature	N/A	N/A	N/A	N/A	N/A

Forests	**Improved and sustainable forest management**	SFM aims to retain substantial levels of biodiversity, carbon, and timber stocks, e.g. through selective logging (Putz et al., 2012). SFM practices often aim at improving ecosystem functionality (Führer, 2000)	Likely contributes to conservation of native pollinators, although literature specifically on SFM and pollinators is small (Potts et al., 2010)	Trees remove air pollution by the interception of particulate matter on plant surfaces and the absorption of gaseous pollutants through the leaf stomata, with significant benefits to human health (Nowak, Hirabayashi, Bodine, & Greenfield, 2014)	Moderate mitigation benefits globally, up to about 2 Gt CO_2e yr^{-1} (Grassi, Pilli, House, Federici, & Kurz, 2018; Griscom et al., 2017; Roe et al., 2019)	Mitigation potential will reduce ocean acidification.	Due to evapotranspiration, trees recharge atmospheric moisture, contributing to rainfall locally and in distant location, and microbial flora and biogenic VOCs associated with some trees can directly promote rainfall (Arneth et al., 2010; Ellison et al., 2017) Trees enhance soil infiltration and, under suitable conditions, improve groundwater recharge (Calder, 2007; Ellison et al., 2017; Neary, Ice, & Jackson, 2009). Many SFM practices are explicitly aimed at water supply improvement (Creed, Sass, Buttle, & Jones, 2011)	Forests tend to maintain water quality by reducing runoff and trapping sediments and nutrients (Idris Medugu, Rafee Majid, Johar, & Choji, 2010; Salvati, Sabbi, Smiraglia, & Zitti, 2014) Precipitation filtered through forested catchments delivers purified ground and surface water co-benefits (Calder, 2007; Ellison et al., 2017; Neary et al., 2009). Many SFM practices are explicitly aimed at water quality improvement (Creed et al., 2011)	Forests counteract wind-driven degradation of soils and contribute to soil erosion protection and soil fertility enhancement for agricultural resilience (Locatelli, Pavageau, et al. 2015), although not often explicitly managed for in SFM	Forest cover can stabilise land against land against catastrophic movements or intense run-off during storms and flood events. (B. Locatelli, Pavageau, et al., 2015). However, reducing harvesting rates and prolonging rotation periods in SFM may induce an increased vulnerability of stands to external disturbances (Yousefpour et al., 2018)	Forests can contribute to pest control and landscape diversity generally improves opportunities for biological pest control (Jactel et al., 2017), although not necessarily directly linked to SFM. Some intensive forest management practices increase pest infestations (Jactel, Brockerhoff, & Duelli, 2005)	SFM may increase availability of biomass for energy, depending on management goals (Kraxner et al., 2013; Sikkema et al., 2014)	Complex relationship between food and forests. On positive side, many millions of households rely on nutrients sourced from forests (Rowland, Ickowitz, Powell, Nasi, & Sunderland, 2017; Wunder, Angelsen, & Belcher, 2014). On negative side, proximity of forest to cropland can increase crop raiding by wild animals (Few, Martin, & Gross-Camp, 2017)	Forests provide many non-wood additional materials (Locatelli, Catterall, et al., 2015), although SFM practices are not necessarily aimed at these other materials	Forests provide medicinal and other resources (Wunder et al., 2014) although not necessarily directly linked to SFM	Natural forest ecosystems often inspire learning (Schultz & Lundholm, 2010; Turtle, Convery, & Convery, 2015) although not necessarily directly linked to SFM	Forests in general support psychological wellbeing (Coldwell & Evans, 2018). Evidence that SFM can improve the cultural and recreational value of ecosystems (Knoke et al., 2014; Plieninger et al., 2015)	Many natural forest landscapes support cultural identities for indigenous peoples (Bolaños, 2011; Garí, 2001), although not linked directly to SFM practices	Many SFM practices are aimed at preserving genetic diversity (Rajora & Mosseler, 2001)

	Reduced deforestation and degradation	Reduced deforestation can enhance connectivity between forest areas and conserve biodiversity hotspots, but there are major argument in literature if REDD+ mechanism sufficiently prioritizes biodiversity over carbon (Gardner et al., 2012; Panfil & Harvey, 2016)	Reduced deforestation contributes to conservation of native pollinators (Priess et al., 2007; Winfree, Bartomeus, & Cariveau, 2011) although no literature specifically on REDD	Standing forests improve air pollution by the interception of particulate matter (Nowak et al., 2014) although no literature specifically on REDD	Large technical mitigation potential of 0.4-5.8 Gt CO_2e yr^{-1} from REDD (Griscom et al., 2017; Houghton & Nassikas, 2018; Roe et al., 2019)	Mitigation potential will reduce ocean acidification.	Standing forests contribute to rainfall locally and in distant locations, and microbial flora and biogenic VOCs associated with some trees can directly promote rainfall (Arneth et al., 2010; Ellison et al., 2017) Trees enhance soil infiltration and, under suitable conditions, improve groundwater recharge (Calder, 2007; Ellison et al., 2017; Neary et al., 2009)	Standing forests tend to maintain water quality by reducing runoff and trapping sediments and nutrients (Idris Medugu et al., 2010; Salvati et al., 2014) Precipitation filtered through forested catchments delivers purified ground and surface water co-benefits (Calder, 2007; Ellison et al., 2017; Neary et al., 2009)	Intact forests counteract wind-driven degradation of soils, and contribute to soil erosion protection and soil fertility enhancement for agricultural resilience (Locatelli, Pavageau, et al., 2015).	Localized hazards like drought, floods and duststorms can be ameliorated by diverse tree cover, which would be encouraged by reduced deforestation (Cooper-Ellis et al. 2009; Jactel et al., 2017; Locatelli, Pavageau, et al., 2015)	Standing forests can contribute to pest control and landscape diversity generally improves opportunities for biological pest control (Jactel et al., 2017)	Reduced deforestation may increase standing wood stocks, but availability depends on what restrictions are in place for management; REDD can also increase competition with biofuel for land (Persson, 2012)	Complex relationship between food and forests. Many millions of households rely on nutrients sourced from forests (Rowland et al., 2017), therefore REDD has potential to benefit but only if not in competition for cropland production and there are compensation for any losses of land (Luttrell, Sills, Aryani, Ekaputri, & Evinke, 2018). Much uncertainty about how REDD actually works on ground.	Forests provide many non-wood additional materials (Locatelli, Catterall, et al., 2015), however, REDD could restrict access to some resources	Reduced deforestation can protect forest medicinal plants (Arnold & Pérez, 2001) as long as REDD policies do not restrict access.	Natural forest ecosystems often inspire learning (Schultz & Lundholm, 2010; Turtle et al., 2015) although not necessarily directly linked to REDD	Forests in general support psychological wellbeing (Coldwell & Evans, 2018). Forests often support recreational opportunities (Liddle, 1997), although not necessarily directly linked to REDD	Many natural forest landscapes support cultural identities for indigenous peoples (Bolaños, 2011; Garí, 2001); however, REDD has been controversial among some indigenous groups who fear it commodifies nature (Lemaitre, 2011; Van Dam, 2011)	Reducing deforestation will likely preserve forest genetic diversity (Rajora & Mosseler, 2001)
	Re-forestation and forest restoration	Forest landscape restoration specifically aims to regain ecological integrity in deforested or degraded forest landscape (Maginnis & Jackson, 2007; Stanturf, Palik, Williams, Dumroese, & Madsen, 2014) However, reforestation with non-native species do not provide same biodiversity benefits (Brundu & Richardson, 2016; Hulvey et al., 2013)	Restoration and reforestation likely contributes to native pollinators if native forest species used (Winfree et al., 2011)	Reforestation is being suggested as novel strategy to combat ground level ozone and other pollutants (Kroeger et al., 2014)	Large technical mitigation potential of 1.5-10.1 Gt CO_2e yr^{-1} (Bastin et al., 2019; Griscom et al., 2017; Roe et al., 2019)	Mitigation potential will reduce ocean acidification.	Literature is mixed on reforestation and restoration impacts on water flow. 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	Reforestation impacts on water quality depend on tree species and planting methods but tend to be positive (Mansourian, Vallauri, & Dudley, 2005). China has seen large increases in water quality linked to national reforestation and restoration (Zhou et al., 2017)	Forest restoration with native species contributes to improved soil hydrological functions and soil fertility (Locatelli, Pavageau, et al., 2015); Perkins, Nimmo, & Medeiros, 2012) ; reforestation also tends to reduce soil erosion over time (Zheng et al., 2008)	Reforestation is commonly used to stabilise land against landslides and flood events. (Laurance, 2007; Phillips & Marden, 2012). However, reforested systems can be vulnerable to natural disasters like wind throws, fires, and diseases	Reforestation is often vulnerable to pest outbreaks (Alfaro & Glover, 1989)	Reforestation can increase availability of biomass for energy (Swisher, 1994)	Competition for land between reforestation and agricultural production is a potentially large adverse side-effect (Boysen et al., 2017; Kreidenweis et al., 2016; P. Smith et al., 2013) that can lead to increases in food prices (Calvin et al., 2014; Kreidenwei	Reforestation can provide other materials (Locatelli, Catterall, et al., 2015)(Le, Smith, Herbohn, & Harrison, 2012)	Forest restoration can increase medicinal supply although needs to be explicit goal (H. S. Lee, 2004)	Reforestation offers opportunities to engage public in learning opportunities (Lazos-Chavero et al., 2016; Mello, Townsend, & Filardo, 2010)	Forests in general support psychological wellbeing (Coldwell & Evans, 2018). Public support for reforestation can increase when recreation and tourism opportunities are explicitly included (Gordon & Barton, 2015), and recreation can increase the value of reforested areas (Zandersen,	Restoration is increasingly including cultural identity and cultural ecosystems services as goals (Agnoletti, 2014) and can provide benefits to participating communities (Reyes-	Restoration can improve genetic diversity if explicitly included in reforestation planning (Thomas Ledig & Kitzmiller, 1992)

		Animal use of restored landscapes for habitat depends on the sensitivity individual species to forest degradation (Budiharta et al., 2014)					implications for fresh water supply (Ciccarese, Mattsson, & Pettenella, 2012; Suding et al., 2015). However, reforestation also can have adverse side-effects for reduction of water yield and water availability, dependent on species and scale (Calder, 2007; Filoso, Bezerra, Weiss, & Palmer, 2017)			(Nolan et al., 2018)			s et al., 2016; Reilly et al., 2012; Wise et al., 2009). Restoration could increase forest food availability, however.				Termansen, & Jensen, 2005)	García et al., 2019)	
	Afforest-ation	Afforestation alone is not sufficient to increase abundance of indigenous species and habitat, as depends on type of vegetation, scale of the land transition, and time required for a population to establish (Barry, Yao, Harrison, Paragahawewa, & Pannell, 2014). Monocrop plantations are least successful for habitat but still may be preferable to other land uses (Brockerhoff, Jactel, Parrotta, Quine, & Sayer, 2008; Pawson et al., 2013), unless planted on native ecosystems (e.g. grasslands)	Afforested areas demonstrate lower pollinator diversity than native forests (Armstrong, van Hensbergen, Scott, & Milton, 1996; Olschewski, Klein, & Tscharntke, 2010)	Afforestation in urban areas reduces local air pollution (Kroeger et al., 2014; Pincetl, Gillespie, Pataki, Saatchi, & Saphores, 2013)	Large technical mitigation potential of 1.5-10.1 Gt CO_2e yr^{-1} (Bastin et al., 2019; Griscom et al., 2017; Roe et al., 2019)	Mitigation potential will reduce ocean acidification .	Afforestation using some exotic species can upset the balance of evapotranspiration regimes, with negative impacts on water availability (e.g. groundwater decline) particularly in arid regions (Ellison et al., 2017; Jackson, 2005; Trabucco, Zomer, Bossio, Van Straaten, & Verchot, 2008; J. Turner et al., 2016) Irrigation of forest plantations can increase water consumption (Sterling, Ducharne, & Polcher, 2013)	Water quality benefits depend on where afforesting and with what species, and if plantations require fertilization, which can get into runoff (D. F. Scott, Bruijnzeel, & Mackensen, 2005)	Afforestation is frequently used to counteract land degradation problems (Buongiorno & Zhu, 2014; Yirdaw, Tigabu, & Monge, 2017) (Buongiorno and Zhu 2014). However, afforestation runs the risk of decreasing soil nutrients, especially in intensively managed plantations (Berthrong, Jobbágy, & Jackson, 2009; Berthrong, Schadt, Pineiro, & Jackson, 2009)	Dense plantings in afforestation may be more susceptive to natural disasters like wind damage fires, and diseases (Nambiar, Harwood, & Kien, 2015; Seidl, Schelhaas, Rammer, & Verkerk, 2014)	Afforestation is often vulnerable to pest outbreaks (Ji, Wang, Wang, & An, 2011; van Lierop, Lindquist, Sathyapala, & Franceschini, 2015)	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 (Calvin et al., 2014; Kreidenweis et al., 2016; Reilly et al., 2012; Wise et al., 2009)	Afforestation could increase availability of other materials and benefits (Rueff, Parizot, Israel, & Schwartz, 2008), but NTFPs etc not usually accounted for in plantations and can displace NTFP collection (McElwee, 2009)	Afforestation does not seem to be associated with increased availability of medicinals	Reforestation/afforestation offers learning opportunities (Lazos-Chavero et al., 2016; Mello et al., 2010) dependent on type of activity	Urban tree planting is associated with psychological and physical benefits dependent on type of trees planted (Camacho-Cervantes, Schondube, Castillo, & MacGregor-Fors, 2014; Whitburn, Linklater, & Milfont, 2019)	Afforestation could contribute to cultural benefits but would need to include these component explicitly (Reyes-García et al., 2019)	Plantations and large scale afforestation is not generally genetically diverse and can have negative consequence for genetic drift (Steinitz, Robledo-Arnuncio, & Nathan, 2012) and reduction in genetic diversity in soil microbiology (Berthrong, Schadt, et al., 2009)

	Increased soil organic carbon content	Improving soil carbon can increase overall land productivity and (more indirectly) contribute to habitat maintenance (Tscharntke et al., 2005); practices that increase soil carbon also likely benefit soil biodiversity (Bender et al., 2016)	N/A	N/A	Mitigation potential of 1.3–5.1 $GtCO_2e\ yr^{-1}$ (P. Smith et al., 2008)	Mitigation potential will reduce ocean acidification. Rivers also transport dissolved organic matter to oceans (Hedges, Keil, & Benner, 1997) but unclear if improved soil organic carbon will affect this	Soil organic matter is known to increase water filtration with positive impacts on downstream flows (Keesstra et al., 2016)	Soil organic matter is known to improve water filtration and protects water quality (Lehmann & Kleber, 2015)	Increasing soil organic carbon contributes substantially to healthier soils (Lehmann & Kleber, 2015; Paustian et al., 2016)	N/A	Increased soil organic carbon decreases pathogens in soil (Lehmann & Kleber, 2015)	N/A	Increased soil organic carbon offers one of best mitigation options with minimal food security impacts (Frank et al., 2017) as it improves food production yields (R. Lal, 2006)	In terms of raw materials, numerous products (e.g. pharmaceuticals, clay for bricks and ceramics, silicon from sand used in electronics, and other minerals) are provided by healthy soils (SSSA, 2015) although not directly related to soil organic carbon management	Some pharmaceuticals can be derived from soils (SSSA, 2015) although not directly related to soil carbon management. Genetic variability in microbial activity likely higher with soil organic carbon (Keesstra et al., 2016)	N/A	N/A	N/A	N/A
	Reduced soil erosion	Managing for soil erosion indirectly decreases need for expanded cropland into natural habitats (Pimentel et al., 1995)	N/A	Particulate matter pollution, a main consequence of wind erosion, imposes severe adverse impacts on materials, structures and climate particularly in urban areas (Al-Thani, Koç, & Isaifan, 2018)	N/A	N/A	Many practices to reduce soil erosion tend to positively improve water flow (Pimentel et al., 1995)	Many practices to reduce soil erosion (e.g. conservation tillage) indirectly improve water quality (Pimentel et al., 1995)	Less eroded soils are higher quality (Keesstra et al., 2016)	Reducing soil erosion reduces vulnerability to hazards like wind storms in dryland areas and landslides in mountainous areas (El-Swaify, 1997)	N/A	N/A	Soil erosion often leads to decreased food production (Pimentel et al., 1995) and yields often go up under some conservation regimes (Ghosh et al., 2010).	N/A	N/A	N/A/	N/A	N/A	N/A
Soils	**Reduced soil salinisation**	Soil salinization (eg. , downriver from irrigation/ dams) negatively impacts ecosystem functioning, soil biodiversity, and can increase susceptibility to invasive species (Nilsson & Berggren, 2000)	N/A	N/A	N/A	N/A	N/A	Management of soil salinity improves water quality (Kotb, Watanabe, Ogino, & Tanji, 2000; Soane & Van Ouwerkerk, 1995; Zalidis, Stamatiadis, Takavakoglou, Eskridge, & Misopolinos, 2002)	Management of soil salinity directly improves soil quality (Keesstra et al., 2016)	N/A	N/A	N/A	Reversing soil degradation contributes to food productivity and reduces food insecurity (Pimentel et al., 1995; Shiferaw & Holden, 1999)	N/A	Salinisation decreases soil microbial diversity (Nie et al., 2009); reversing it improves genetic resources	N/A	N/A	N/A	N/A

	Reduced soil compaction	Preventing compaction indirectly decreases need for expanded cropland into natural habitats (Lal, 2001; Pimentel et al., 1995)	N/A	N/A	N/A	N/A	Compaction can increase water runoff - management of soil compaction improves water quantity (Soane & Van Ouwerkerk, 1995; Zalidis et al., 2002)	Management of soil compaction improves water quality (Soane & Van Ouwerkerk, 1995; Zalidis et al., 2002)	Actions to reduce compaction directly 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, Bourrié, & Trolard, 2013); reversing this can lead to increased productivity	N/A	N/A	N/A	N/A	N/A	N/A
	Biochar addition to soil	Biochar production could compete with natural habitat, depending on feedstock used (Meyer, Glaser & Quicker, 2011), but unclear evidence on direct relationship	N/A	Biochar itself has little air quality impact, but depending on kiln technologies, biochar production can create particulate emissions (Sparrevik et al., 2012)	Potential abatement of 0.03 to 6.6 $GtCO_2e$ yr^{-1} (Hawken, 2017)	Mitigation potential will reduce ocean acidification	Biochar tends to improve soil water filtration and retention, thus can improve downstream flows (Beck, Johnson, & Spolek, 2011; Spokas et al., 2012)	Biochar can improve soil water filtration, thus impacting quality (Beck et al., 2011; Spokas et al., 2012)	Biochar can improve soil quality through addition of nutrients and stimulating microbial activity (Sohi, 2012; Jones, Rousk, et al. 2012)	N/A	N/A	N/A	Biochar addition can increases food yields, depending on context (Jeffery et al., 2017; P. Smith, 2016); however, biochar production could compete with croplands, depending on feedstock used (Meyer, Glaser & Quicker, 2011)	N/A	N/A	N/A	N/A	N/A	N/A
	Fire manage-ment	Proactive fire management can improve and preserve natural habitat (Burrows, 2008)	Reducing fire risk may improve habitat for pollinators (Brown, York, Christie, & Mccarthy, 2016)	Fire management improves air quality, particularly in the periurban interface (Bowman & Johnston, 2005)	Total emissions from fires have been in the order of 8.1 $GtCO_2e$ yr^{-1}, therefore some fraction of that can be reduced (Arora and Melton 2018; Tacconi 2016)	Mitigation potential will reduce ocean acidification	Fires affect water quality and flow due to erosion exposure (Townsend & Douglas, 2000), therefore reduction in fire hazard should improve	Fires affect water quality and flow due to erosion exposure (Townsend & Douglas, 2000), therefore reduction in fire hazard should improve	Fire causes damage to soils, therefore fire management can reduce this (Certini, 2005)	Will reduce risk of wildfires as a major human hazard (McCaffrey, 2004; Kumagai, Caroll & Cohn, 2004)	Some benefits to pest control from fire management (Hardison, 1976)	Will increase availability of biomass, as fuel removal is a key management strategy (Becker, Larson, & Lowell, 2009)	N/A	N/A	N/A	N/A	Reduced wildlife risk will increase recreation opportunities in landscapes (Venn & Calkin, 2011)	N/A	N/A
Other ecosystems	**Reduced landslides and natural hazards**	Fewer landslides can preserve natural habitat (Dolidon, Hofer, Jansky, & Sidle, 2009)	N/A	N/A	N/A	N/A	Practices to reduce landslides (eg vegetation cover) will likely improve water flow (Dolidon et al., 2009)	Practices to reduce landslides (eg vegetation cover) will likely improve water quality (Dolidon et al., 2009)	Practices to reduce landslides (eg vegetation cover) will likely improve soil quality (Keesstra et al., 2016)	Fewer landslides strongly reduces risk of disasters (Dolidon et al., 2009; Kousky, 2010)	N/A	N/A	Landslides can have negative 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, Kasian, & Hesslein, 1989)	Pollution interferes with scents, which impact pollinators ability to detect resources (McFrederick, Kathilankal, & Fuentes, 2008)	Reducing pollution will improve air quality with public health benefits (Nemet, Holloway, & Meier, 2010)	Climate impacts in two channels: reduce projected warming ~0.5ºC by 2050 and 2) N deposition affects terrestrial C uptake 0.55-1.28 $GtCO_2e\ yr^{-1}$ (Bala, Devaraju, Chaturvedi, Caldeira, & Nemani, 2013; Shindell et al., 2012)	Mitigation potential will reduce ocean acidification	N/A	Pollution increases acidity of surface water (Larssen et al., 1999); less pollution improves water quality	Soil acidification due to air pollution in a serious problem in many countries (Tian & Niu, 2015); less pollution will reduce this	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Manage-ment of invasive species / encroach-ment	Many invasive alien species (IAS) diminish biodiversity; improved management of IAS can lead to improved habitat and ecosystems (Richardson & Wilgen, 2004)	Invasive species can disrupt native plant-pollinator relations (Vanbergen, Espíndola, & Aizen, 2018)	N/A	N/A	N/A	Many invasives can reduce water flow (Richardson & Wilgen, 2004)	Invasive freshwater species can reduce water quality (Burnett, Kaiser, & Roumasset, 2007; Chamier, Schachtschneider, Le Maitre, Ashton, & Van Wilgen, 2012)	Likely to improve soil as invasive species generally have negative effects on soils (Ehrenfeld & Scott, 2001)	N/A	Many IAS are considered 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 IAS are important suppliers of useful materials (Pejchar & Mooney 2009).	N/A	N/A	N/A	N/A	Reducing IAS can increase biological diversity of native organisms (Simberloff, 2005)
	Restoration and avoided conversion of coastal wetlands	Coastal wetlands are important natural habitats (Griscom et al., 2017; J. Howard et al., 2017)	Coastal wetlands contain many natural pollinators (Seddon et al., 2016)	N/A	Mitigation potential of 0.3-3.1 $GtCO_2e\ yr^{-1}$ (Griscom et al., 2017; Pendleton et al., 2012)	Mitigation potential will reduce ocean acidification .	Wetlands store freshwater and enhance water flow (Bobbink, Whigham, Beltman, & Verhoeven, 2006)	Wetlands strongly filter and enhance water quality (Bobbink et al., 2006)	Wetland conservation actions benefit soil quality (Zhao et al., 2016)	Restoration of wetlands, tidal marshes, or mangroves provide water retention and protect coastal cities from storm surge flooding and shoreline erosion during storms as well as protection against sea level rise (Gittman, Popowich, Bruno, & Peterson, 2014; J.	Natural 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, Herr, Tamelander, & Laffoley, 2011; Pendleton et al., 2012)		Wetlands can be sources of medicines (UNEP, 2016)	Many wetlands serve as living labs for students (Sukhontapatipak & Srikosamatara, 2012)	Wetlands based recreation is very popular and economically valuable (Bergstrom, Stoll, Titre, & Wright, 1990)	Many wetland species serve important cultural roles and contribute to community identity (Davenport et al., 2010; Garibaldi & Turner, 2004)	Biodiversity and genetic diversity in wetlands is a priority for conservation (Denny, 1994)

										Haddad, Lawler, & Ferreira, 2016; Kaplan & Hepcan, 2009)									
	Restoration and avoided conversion of peatlands	Peatlands are important natural habitats (Lindsay, 1993)	Avoided conversion likely conserves natural pollinators although less known directly about peatlands (Winfree et al., 2011)	Conversion of peatlands has been implicated in negative regional smoke and particulate matter emissions (Tacconi 2016)	Mitigation potential of 0.6-2 $GtCO_2e$ yr^{-1} Griscom et al. (2017); Hawken 2017	Mitigation potential will reduce ocean acidification.	Peatland restoration will improve water quantity as play important roles in water retention and drainage (Johnston, 1991)	Peatland restoration will improve water quality as play important roles in water filtration (Johnston, 1991)	Avoided conversion will improve peatland soil quality (Paustian et al., 2016), since conversion leads to degradation	N/A	Natural landscape diversity generally improves opportunities for biological pest control (Gardiner et al. 2009)	Will reduce supply of any bioenergy (e.g. palm oil) sourced from peatlands (Pin Koh, 2007)	May reduce land available for smallholders agriculture in tropical peatlands (Jewitt, Nasir, Page, Rieley, & Khanal, 2014), where food is produced on peatlands	Will reduce supply of some materials sourced from peatlands (e.g palm oil) (Murdiyarso, Hergoualc'h, & Verchot, 2010)	N/A	Peatlands can provide opportunities for learning and other cultural services (Waylen, Noort, & Blackstock, 2016)	European peatlands are sites of recreation (eg berry picking) (Joosten & Clarke, 2002; Tolvanen, Juutinen, & Svento, 2013)	Peatlands can serve as sites of cultural identity and heritage (e.g Scotland) (Byg, Martin-Ortega, Glenk, & Novo, 2017; Faccioli, Czajkowski, Glenk, & Martin, 2018)	Conversion of peatlands leads to loss of soil and plant genetic diversity (Dislich et al., 2017)
	Biodiversity conserve-ation	Biodiversity conservation includes measures aiming to promote species richness and natural habitats e.g. protected areas (Powers & Jetz, 2019) which can also have carbon benefits (Cromsigt et al., 2018)	Biodiverse animal and insect populations are necessary for pollination (Anzures-Dadda, Andresen, Martinez, & Manson, 2011; Beaune, Fruth, Bollache, Hohmann, & Bretagnolle, 2013; Brockerhoff et al., 2017; Brodie & Aslan, 2012; Winfree et al., 2011)	Landscapes ensured by protected areas can remove air pollutants (Sutton et al., 2007), unclear if biodiversity plays any role	Depending on the type of practice and specific context (E.g. protected areas, wildlife corridors, etc) the potential mitigation from protection of these areas for the period 2005-2095 is on average about 0.9 $GtCO_2$-eq. yr^{-1} (Calvin et al., 2014)	Mitigation potential will reduce ocean acidification.	Many actions taken to increase biodiversity (e.g protected areas) can also have incidental effects of improving water quantity (Egoh, Reyers, Rouget, Bode, & Richardson, 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 and nutrient cycling and transport. 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	Management of wild animals can influence fire frequency as grazers lower grass and vegetation densities as potential fuels (Schmitz et al., 2014)	Biological diverse fauna can reduce pest outbreaks (Tscharntke et al., 2007)	N/a	Biodiversity generally has positive effects on crop production (Potts et al., 2010) but expansion of protected areas or wildlife corridors could compete with food production in some areas of tropics (Musters, 2000; Visconti, Bakkenes, Smith, Joppa, & Sykes, 2015)	Expansion of protected areas or wildlife corridors could reduce production and consumption of some materials in strictly protected areas (McElwee, 2010)	Many animals are used as sources of medicines, and genetic diversity is important part of biodiversity conservation (Alves & Rosa, 2007; Neergheen-Bhujun et al., 2017)	Biomimicry is important source of learning (Benyus, 2002)	Biodiversity conservation and protected areas attract ecotourists and have high international value (Brandon, 1996; Lindsey, Alexander, Mills, Romañach, & Woodroffe, 2007)	Indigenous peoples commonly link biodiversity to cultural identities, association with place, kinship ties, customs and protocols, stories, and songs (Gould et al., 2014; Lyver et al., 2017)	Biodiversity conservation explicitly aimed at maintaining options and genetic diversity (Witting & Loeschcke, 1995)

									(Cromsigt et al., 2018; Schmitz et al., 2014, 2018)										
	Enhanced weathering of minerals	N/A	N/A	N/A	Mitigation potential of about 0.5-4 $GtCO_2e\ yr^{-1}$ (Smith et al. 2019)	Mitigation potential will reduce ocean acidification	N/A	May have negative effects on water quality (Atekwana, Atekwana, Legall, & Krishnamurthy, 2005)	Has potential to improve soil quality (Kantola, Masters, Beerling, Long, & DeLucia, 2017; Rau & Caldeira, 1999)	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**	Can reduce areas of natural habitat with negative effects on biodiversity (Hof et al., 2018; Immerzeel et al., 2014)	If natural habitats are decreased due to bioenergy expansion, would reduce natural pollinators (Keitt, 2009)	The use of BECCS could reduce air pollution from use of fossil fuels (IPCC, 2018)	Large mitigation potential depending on scale e.g. up to ~11 $GtCO_2\ yr^{-1}$ (IPCC, 2018; Smith et al., 2020); any local and regional climate effects would be dependent on feedstock, prior land use, scale and location	Bioenergy and BECCS will reduce ocean acidification by reducing CO_2 emissions and concentrations (IPCC, 2018; Doney, Fabry, Feely, & Kleypas, 2009)	Depending on the feedstock, can require water. Models show high risk of water scarcity if BECCS is deployed on widespread scale (Hejazi et al., 2014; Popp, Dietrich, et al., 2011; Smith, Davis, et al., 2016) through both increases in water withdrawals (Bonsch et al., 2015; Hejazi et al., 2014) and changes in surface runoff (Cibin, Trybula, Chaubey, Brouder, & Volenec, 2016)	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, Eheart, Cai, & Miguez, 2010) and others showing declines (Sinha, Michalak, Calvin, & Lawrence, 2019)	Will likely decrease soil quality if exotic fast growing trees used (Humpenöder et al., 2018; 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)	Large scale deployment of bioenergy and BECCS can lead to significant trade-offs with food production and significantly higher food prices given large-scale land conversion (Humpenöder et al., 2018; Popp et al., 2017; Smith, Davis, et al., 2016)	If bioenergy and BECCS drive land use conversion (Humpenöder et al., 2018; Smith et al., 2016; Clarke et al., 2014; Popp et al., 2017), it can reduce opportunities for production of other materials	If bioenergy and BECCS drive land use conversion (Humpenöder et al., 2018; Smith, Davis, et al., 2016; Clarke et al., 2014; Popp et al., 2017), it can reduce genetic resources	If bioenergy and BECCS drive land use conversion (Humpenöder et al., 2018; Smith, Davis, et al., 2016; Clarke et al., 2014; Popp et al., 2017), it can reduce opportunities for learning and inspiration	If bioenergy and BECCS drive land use conversion (Humpenöder et al., 2018; Smith, Davis, et al., 2016; Clarke et al., 2014; Popp et al., 2017), it can reduce opportunities for recreation & tourism	If bioenergy and BECCS drive land use conversion (Humpenöder et al., 2018; Smith, Davis, et al., 2016; Clarke et al., 2014; Popp et al., 2017), it can reduce culturally significant landscapes	If bioenergy and BECCS drive land use conversion (Humpenöder et al., 2018; Smith, Davis, et al., 2016; Clarke et al., 2014; Popp et al., 2017), it can 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**
	Dietary change	Can lead to reduced expansion of agricultural lands, which can spare/increase natural habitat (Tilman et al., 2001; Laroche et al., 2020), as well as encourage diversified systems (Kremen et al. 2012; Allen et al., 2014). Models of future trends show better outcomes for habitat and biodiversity from sustainable diets (Henry et al., 2019)	Demand for more vegetables will likely encourage pollinator-friendly practices (Laroche et al., 2020); indirect impact from sparing of lands which will likely positively increase pollinators (since they are negative effected by intensive food systems, Kremen, Williams & Thorpe, 2002);	Some possible positive indirect effects from land sparing or reduced local emissions but unexplored in literature.	Mitigation potential of 0.7-8 $GtCO_2\ yr^{-1}$ due to avoided land use conversion of reduced demand (Hawken, 2017; Popp, Lotze-Campen, & Bodirsky, 2010)	Mitigation potential will reduce ocean acidification.	Will likely reduce water consumption if less water-intensive food/livestock needs to be produced (Tilman et al., 2001; Allen et al., 2014)	Reduced meat consumption will improve water quality due to fewer livestock, which are water polluting (Stoll-Kleemann & O’Riordan, 2015)	Indirect impact: Sparing of lands and changes in nutrient input likely will positively increase soil quality (Willet et al. 2019), though no direct literature on dietary change alone	N/A	Indirect impact: More sustainable diets likely will lead to less pest outbreaks due to more diversified agriculture (Kremen et al., 2012), but not well quantified in lit.	N/A	Will help increase global food supplies by decreasing demand for high intensity diets (particularly reducing land needed for feed for livestock) (Kastner, Rivas, Koch, & Nonhebel, 2012; Willet et al., 2019)	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.
Demand management	**Reduced post-harvest losses**	Will lead to reduced expansion of ag lands, which can preserve natural habitat (Tilman et al., 2001), although not well quantified in lit for post-harvest losses specifically	Indirect positive impact from sparing of lands (Kremen, Williams & Thorpe, 2002);	N/A	Mitigation potential of 4.5 $GtCO_2\ yr^{-1}$ (Bajželj et al., 2014)	Mitigation potential will reduce ocean acidification	Will reduce water consumption if less food/livestock needs to be produced (Tilman et al., 2001; Allen et al., 2014)	Reduced food production will reduce N fertiliser use, improving water quality (Kibler, Reinhart, Hawkins, Motlagh, & Wright, 2018)	Indirect impact: Sparing of lands and changes in nutrient input likely will positively increase soil quality (Willet et al. 2019), though no direct literature on post-harvest losses alone	N/A	Reducing postharvest losses usually include positive measures to deal with pests (e.g. integrated pest manage-ment) (Wilson & Pusey, 1985)	Possible indirect effect in that post-harvest losses may be used for biomass energy if not edible/sold, but no literature	Will help increase global food supplies since waste accounts for 25% of total production (Kastner et al., 2012)	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.

	Reduced food waste (consumer or retailer)	Improved storage and distribution reduces food waste and the need for compensatory intensification of agricultural areas (land sparing) and land use change (Stathers, Lamboll, & Mvumi, 2013)	Indirect positive impact from sparing of lands (Kremen, Williams & Thorpe, 2002)	N/A	Mitigation potential of 0.8 to 4.5 $GtCO_2\,yr^{-1}$ ((Bajželj et al., 2014; Hawken, 2017; Hiç, Pradhan, Rybski, & Kropp, 2016)	Mitigation potential will reduce ocean acidification.	Will reduce water consumption if less water-intensive food/livestock needs to be produced (Tilman et al., 2001; Allen et al., 2014))	Reduced food production will reduce N fertiliser use, improving water quality (Kibler et al., 2018)	Indirect impacts on soil (see above)	N/A	N/A	N/A	Will help increase global food supplies since waste accounts for 25% of total production (Kastner et al., 2012)	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.	Some possible positive indirect effects from land sparing but unexplored in literature.
	Material substitution	Material substitution increases demand for wood, which can lead to loss of habitat (Sathre & Gustavsson, 2006)	N/A	N/A	Possible mitigation potential of 0.25 to 1 $GtCO_2\,yr^{-1}$ (Oliver, Nassar, Lippke, & McCarter, 2014)	Mitigation potential will reduce ocean acidification	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	Commodity production is responsible for nearly 40% of deforestation (Henders, Persson, & Kastner, 2015). Forest certification and other sustainable sourcing schemes can reduce habitat fragmentation as compared to conventional supply chains (Rueda, Thomas, & Lambin, 2015)	Possible indirect benefits due to improved ecosystem management but no literature	Forest certification improved air quality in Indonesia by 5% due to reduced incidence of fire for palm oil due to zero deforestation pledges (Miteva, Loucks, & Pattanayak, 2015)	No quantified evidence but likely some mitigation benefits	N/A	Forest certification has led to improved water flow due to decreased road construction for logging (Miteva et al., 2015)	Forest certification has improved riparian waterways and reduced chemical inputs in some schemes (Rueda et al., 2015)	Possible indirect benefits due to improved ecosystem management but no literature	Possible indirect benefits due to improved ecosystem management but no literature	Possible indirect benefits due to improved ecosystem management but no literature	Sustainable sourcing can supply energy like biomass more sustainably (Sikkema et al., 2014)	Sustainable sourcing can encourage more production of high quality food due to price premiums (e.g. organic standards) (G. Smith, 2008); however, one study found increased food insecurity among indigenous peoples near a forest certification site (Doremus 2019)	Sustainable sourcing is increasingly important in supply of timber and other materials production (Irland, 2008)	Sustainable sourcing can supply medicinals, e.g. bioprospecting (Pierce & Laird 2003).	Possible indirect benefits due to improved ecosystem management but no literature	Possible indirect benefits due to improved ecosystem management but no literature	Comparative studies show community involvement in certification and standards for sustainable sourcing has been low (Pinto & McDermott 2013; Vandergeest 2007) thereby not strengthening community identities	Possible indirect benefits due to improved ecosystem management but no literature
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 access to global food supplies (Hamprecht, Corsten, Noll, & Meier, 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

		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
	Enhanced urban food systems	Urban gardening can improve habitat and biodiversity in cities (Lin, Philpott, & Jha, 2015; Orsini et al., 2014)	Urban beekeeping has been important in keeping pollinators alive in cities (Gunnarsson & Federsel, 2014)(	Urban agriculture can increase vegetation cover and improve air quality in urban areas (Cameron et al., 2012; Lin et al., 2015)	N/A	N/A	Water access often a constraint on urban agriculture and can increase demands (Badami & Ramankutty, 2015; de Bon, Parrot, & Moustier, 2010)	Urban agriculture can exacerbate urban water pollution problems (pesticide runoff, etc) (Pothukuchi & Kaufman, 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)	Urban food systems can supply other useful materials (Lin et al., 2015)	Many urban foods also have medicinal and health properties (Madaleno, 2000; Poe, McLain, Emery, & Hurley, 2013)	Urban agriculture can be used for teaching and learning (Travaline & Hunold, 2010)	Urban gardening provides physical benefits of being outdoors (Soga et al., 2017)	Urban agriculture can promote positive cultural identities (Baker, 2010)	Urban food can contribute to preserving local genetic diversity (Lin et al., 2015)
	Improved food processing and retail	Indirect benefits from less waste (see reduced food loss above)	Indirect benefits from less waste (see reduced food loss above)	Improved processing and retailing may reduce energy use associated with transport and storage, leading to less air pollution (Papadopoulos & Seferlis, 2013)	Indirect benefits from less waste (see reduced food loss above)	Indirect benefits from less waste (see reduced food loss above)	Improved processing and retailing may reduce water consumption associated with food processing (Nemecek, Jungbluth, Canals, & Schenck, 2016)	Indirect benefits from less waste (see reduced food loss above)	N/A	N/A	N/A	N/A	Improved food processing may increase food access, freshness and availability (Clark, Jung, & Lamsal, 2014)	N/A	N/A	N/A	N/A	N/A	N/A
	Improved energy use in food systems	N/A	N/A	Improved energy use will lead to less local air pollution (Usubiaga-Liaño, Behrens, & Daioglou, 2020)	Small mitigation potential of 0.37 $GtCO_2\ yr^{-1}$ (James & James, 2010; Vermeulen, Campbell, & Ingram, 2012; (Usubiaga-Liaño, Behrens, & Daioglou, 2020)	Mitigation potential will reduce ocean acidification	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**	**Support-ing identities**	**Main-tenance 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 in many cities worldwide (Frumkin, 2002)	Likely some but unquantified mitigation benefits	N/A	Managing urban sprawl can increase water availability in cities (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, Xia, Clarke, & Frei, 2007)	Likely to be very beneficial for soils as soil sealing is major problem in urban areas (Scalenghe & Marsan, 2009)	N/A	N/A	N/A	Urban sprawl often competes with land for food production and can reduce overall yields (Barbero-Sierra, Marques, & Ruíz-Pérez, 2013; J. Chen, 2007)	N/A	N/A	N/A	N/A	N/A	N/A
	Livelihood diversification	Could have indirect impacts if diversification allows land sparing or reduction in land conversion, but no literature	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 (A. 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 through agricultural expansion and intensification; local seeds likely better (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 they are suited to local environments (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 and with lower tillage (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 (Bisht et al., 2018; Coomes et al., 2015). However local seeds often are less productive than improved commercial varieties.	Local seeds can produce multifunctional materials (Adhikari, 2014).	Many local seeds can have multiple functions, including producing medicinals (Hammer & Teklu, 2008)	Passing on seed information is important cultural learning process (Coomes et al., 2015)	N/A	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	Many habitats confer disaster protection (Kousky 2010), and some DRM strategies may include habitat protection explicitly for a positive benefit (Shreve & Kelman 2014) (e.g. mangrove protection, addressed above under	N/A	N/A	N/A	N/A	N/A	N/A	Some DRM strategies do have a soil conservation focus (Shreve & Kelman 2014) (addressed above in reduced soil erosion benefits), but otherwise unknown relationship.	DRM is one of the most effective ways to help people avoid extreme events and adapt to climate change (Mechler et al., 2014)	N/A	N/A	Early warning systems and other DRM measures can help avert food shortages e.g. from drought (Genesio et al., 2011; Hillbruner & Moloney, 2012)	N/A	N/A	N/A	N/A	DRM with an explicit cultural focus could help manage/ protect ecosystems to support identified but unclear how widespread or effective	N/A

		restoration and avoided conversion of wetlands), but unclear how extensive DRM benefiting habitats is																	
	Risk sharing instruments	Commercial crop insurance often encourages habitat conversion; (Wright & Wimberly, 2013) found half million 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 negatively impact natural pollinators due to incentives for production (Horowitz & Lichtenberg, 1993)	N/A	Some mitigation benefits from not using commercial crop insurance, which encourages agricultural expansion (Claassen, Carriazo, Cooper, Hellerstein, & Ueda, 2011)	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 increases 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 (Roger Claassen, Cooper, & Carriazo, 2011; Goodwin, Vandeveer, & Deal, 2004)	N/A	Insurance encourages monocropping leading to loss of genetic diversity for future (Glauber, 2004)	N/A	N/A	N/A	Insurance encourages monocroppi ng, 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

		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**
Agri-culture	**Increased food productivity**	Increasing farm yields for smallholders contributes to poverty reduction (Irz, Lin, Thirtle, & Wiggins, 2001; J. N. Pretty et al., 2003; A. Smith et al., 2017)	Increasing farm yields for smallholders reduces food insecurity (Irz, Lin, Thirtle, & Wiggins, 2001; J. N. Pretty et al., 2003)	Increased food productivity leads to better health status for farmers (Dar & Laxmipathi Gowda, 2013; Rosegrant & Cline, 2003); low farm productivity is associated with lower calorie intact among women farmers (Agarwal, 2018)	N/A	Increased productivity can benefit female farmers, who make up 50% of agricultural labor in sub-Saharan Africa (Ross, Zereyesus, Shanoyan, & Amanor-Boadu, 2015) Low farm productivity is associated with lower calorie intact among women farmers (Agarwal, 2018)	Food productivity increases could impact water quality if increases in chemicals used, but evidence is mixed on sustainable intensification (Mueller et al., 2012; Rockström et al., 2009)	N/A	Increased agricultural production contributes to increased economic growth (Springmann et al., 2016).	N/A	Increased agricultural production can contribute to reducing inequality among smallholder s (Datt & Ravallion, 1998)	Increased food production can increase urban food security (Ellis & Sumberg, 1998)	N/A	Increased production can increase adaptability to climate change (Pretty et al. 2018). Also see Table SM1, regulation of climate for mitigation benefits	Increased food productivity might be achieved through increased pesticide or fertiliser use, which causes runoff and dead zones in oceans (Beusen et al., 2016); some positive benefits from reduced ocean acidification associated with	Higher productivity spares land (e.g. Balmford et al. 2018) especially if intensification is done sustainably; conventional intensification associated with biodiversity and habitat loss (Beckmann et al. 2019) (see Table 1)	N/A	Improved agricultural productivity generally correlates with increases in trade in agricultural goods (Fader, Gerten, Krause, Lucht, & Cramer, 2013)

															mitigation potential			
	Improved cropland management	Improved cropland management increases yields for smallholders and thus can contribute to poverty reduction (Irz et al., 2001; J. N. Pretty et al., 2003; K. Schneider & Gugerty, 2011)	Conservation agriculture contributes to food productivity and thus can reduce food insecurity (Dar & Laxmipathi Gowda, 2013; Godfray & Garnett, 2014; Rosegrant & Cline, 2003)	Conservation agriculture contributes to improved health through several pathways, including reduced fertiliser/ pesticide use which cause health impacts e (Erisman, Galloway, Seitzinger, Bleeker, & Butterbach-Bahl, 2011) as well as improved food security, but less lit on this.	N/A	N/A	Cropland management practices such as conservation tillage improve downstream and groundwater water quality and good management practices can substantially decrease P losses in water (Fawcett et al., 1994; Foster, 2018)	N/A	Improved cropland management can contribute to increased economic growth, mainly in improvements in smallholder agriculture (Abraham & Pingali, 2017)	N/A	Improved cropland managemen t leading to increased agricultural production can contribute to reducing inequality among smallholder s (Abraham & Pingali, 2017; Datt & Ravallion, 1998)	N/A	Improved conservation agriculture can contribute to sustainable production goals (Hobbs, Sayre, & Gupta, 2008)	Better cropland management as an adaptation strategy can impact millions (Challinor et al., 2014; Lipper et al., 2014; Lobell, Baldos, & Hertel, 2013; Vermeulen, Aggarwal, et al., 2012) Also see Table SM1, regulation of climate for mitigation potential	Some acidification reduction potential, but covered in table S1. Other ocean impacts unknown	Improved cropland management can contribute to diverse agroecosyste ms (Tscharntke, Klein, Kruess, Steffan-Dewenter, & Thies, 2005) and promotes soil biodiversity (Oehl, Laczko, Oberholzer, Jansa, & Egli, 2017) (see Table 1)	N/A	N/A
	Improved grazing land management	Can increase productivity for smallholder pastoralists and contribute to poverty reduction (Boval & Dixon, 2012)	Improved grazing management can contribute to food security (O'Mara, 2012)	Improved livestock and grazing management could contribute to better health among smallholder pastoralists (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, Place, Ehui, & Institute., 2006)	N/A	Improved pastoral managemen t 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)	Could benefit up to 25 million people as an adaptation strategy Porter et al. 2014. Also see Table SM1, regulation of climate	Some acidification reduction potential, but covered in table S1. Other ocean impacts unknown	Can contribute to improved habitat for other species (Pons, Lambert, Rigolot, & Prodon, 2003; Plantureux, Peeters, & McCracken, 2005), reverse soil degradation, etc (see Table 1)	Grazing land managemen t 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 (K. E. V. Hooft et al., 2012)	Improved livestock management can contribute to reduced food insecurity among smallholder pastoralists (K. E. V. Hooft et al., 2012)	N/A	N/A	N/A	Improved livestock production can reduce water contamination (e.g. reduced effluents) (Hooda et al., 2000) through manure management (Herrero & Thornton, 2013)	N/A	Improved livestock management can increase economic productivity and employment opportunities in global South (Mack, 1993)	N/A	N/A	N/A	Sustainable livestock management contributes to sustainable production goals (De Wit, Oldenbroek, Van Keulen, & Zwart, 1995)	Could benefit up to 25 million people as an adaptation strategy Porter et al. 2014. Also see Table SM1, regulation of climate	Some acidification reduction potential, but covered in table S1. Other ocean impacts unknown	Can contribute somewhat indirectly to improved habitat if more efficient animals used, leading to less feed required (Strassburg et al., 2014)	N/A	Improved livestock productivity would likely correlate with increases in trade (Herrero, Thornton, Gerber, & Reid, 2009)
	Agro-forestry	Agroforestry can be usefully used for poverty reduction, particularly for smallholders (Leakey & Simons, 1997)	Agroforestry contributes to food productivity, nutritious diets, and reduces food insecurity (Mbow, Van Noordwijk, et al., 2014)	Agroforestry positively contributes to nutritious diets (Haddad, 2000); other health benefits not well explored in lit	N/A	Increased use of agroforestry can benefit female farmers as it requires low overhead (Gladwin et al. 2002), but land tenure	Agroforestry can be used to increase ecosystem services benefits, such as water quantity and quality (Jose, 2009)	Agroforestr y can increase biomass production for on-farm energy (Mbow, Van Noordwijk, et al., 2014)	Agroforestry and other forms of employment in forestry make major contributions to global GDP (Pimentel et al., 1997)	N/A	Agroforestr y promotion can contribute to reducing inequality among smallholder s (Leßmeister et al., 2018)	N/A	Agroforestry contributes to sustainable production goals (Mbow, Van Noordwijk, et al., 2014)	Large adaptation benefits for more than a billion people through multiple pathways (Lasco, Delfino, Catacutan, Simelton, & Wilson, 2014; Mbow, Smith, et	Some acidification reduction potential, but covered in table S1. Other ocean impacts unknown	Agroforestry mimics natural diversity and can strongly improve or provide additional habitat, including as conservation	N/A	N/A

						issues must be paid attention to (Kiptot & Franzel, 2012; Kiptot et al..,2014)								al., 2014). Also see Table SM1, regulation of climate		corridors (Jose, 2009; Jose 2012; Bhagwat, Willis, Birks, & Whittaker, 2008), reverse land degradation, etc. (See table 1)		
	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, Pallante, & Palma, 2018; Weinberger & Lumpkin, 2007)	Diversification is associated with increased access to income and additional food sources for the farming household (Ebert, 2014; Pretty et al., 2003).	More diversified agriculture leads to diversified diets which result in better health outcomes (Block & Webb, 2001; Ebert, 2014; Kadiyala, Harris, Headey, Yosef, & Gillespie, 2014)	N/A	Women and children tend to benefit from agricultural diversification due to improved diets (Pretty et al., 2003)	N/A	N/A	Agricultural diversification generally leads to economic growth (Pingali & Rosegrant, 1995; Rahman, 2009)	N/A	Increased agricultural diversification can contribute to reducing inequality among smallholders (Makate, Wang, Makate, & Mango, 2016) although there is mixed evidence of inequality also increasing in commercialised systems (Pingali & Rosegrant, 1995; Weinberger & Lumpkin, 2007)	N/A	N/A	Diversification both increases resilience by spreading risk and provides economic benefits, with adaptation benefits for likely more than 25 million people (Campbell, Thornton, Zougmoré, van Asten, & Lipper, 2014)	N/A	Crop diversification improves resilience through enhanced diversity to mimic more natural systems including functional biodiversity at multiple spatial and/or temporal scales (Kremen, Iles, & Bacon, 2012; Lin, 2011)	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 to poor pastoralists (Foggin, 2008)	Can affect food security when competition for land occurs (O'Mara, 2012)	Indirect health effects from reduced production potentially, but little lit	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, Darwin, Tsigas, & Raneses, 1999)	N/A	N/A	N/A	N/A	Unknown for adaptation; see Table SM 1, regulation of climate, for mitigation	Some acidification reduction potential, but covered in table S1. Other ocean impacts unknown	Is aimed at preserving natural grassland habitat (Peeters, 2009), also has soil benefits and reverses land degradation (see Table 1)	N/A	N/A
	Integrated water management	Various IWM practices contribute to poverty reduction (UNCTAD, 2011); green water harvesting contributes to alleviate poverty	Integrated, efficient, equitable and sustainable water resource management (e.g. water for agroecosystem) plays importance for food production and benefits to	IWM can reduce the global burden of disease and improve health (UNWater, 2015)	N/A	Involving women in IWM initiatives can increase project effectiveness and gender equity (Green & Baden, 1995)	IWM aims to solve watershed problems such as lack of water (quantity), deterioration in water quality, and low output (K. E. Lee et al.,	N/A	Improved water management is considered critical for sustainable socio-economic development (UN Water, 2015).	IWM can increase access of industry to water for economic growth (Rahaman & Varis, 2005)	Better IWM could reduce inequities in access to water, particularly thru community initiatives (Komakech, van der	Water is a limiting factor in urban growth and IWM can help improve access to urban water supplies (Bao & Fang, 2012)	IWM is part of sustainable production in food, water, and energy security (Rasul, 2016)	IWM has large adaptation benefits to help more than 250 million people potentially cope with water shortages Dillon and Arshad 2016; Liu et al. 2017.	IWM on land is likely to improve water quality runoff into oceans (Agboola & Braimoh, 2009)	Ecosystem health and services can be enhanced by improving water management (Bernex, 2016; Boelee, Chiramba, & Khaka, 2011; Jingya Liu et	IWM can reduce conflicts that arise from water scarcity (UN Water, 2015).	IWM encourages partnerships across countries and regions (UN Water, 2015)

		(Rockström & Falkenmark, 2015); improving water irrigation reduces poverty (Rengasamy, 2006)	people (Lloyd et al., 2013)				2018) IWM increases water-use efficiency and ensures sustainable withdrawals to substantially reduce the number of people suffering from water scarcity (UNWater, 2015)				Zaag, &van Koppen, 2012)					al., 2016; Lloyd et al., 2013), and reversing land degradation (e.g. salinization) (see Table 1)		
	Improved and sustainable forest management	May contribute to poverty reduction if conditions are right (Blomley & Ramadhani, 2006; Donovan, Stoian, Macqueen, & Grouwels, 2006) but conflicting data, as it may also favour large landowners who are less poor (Rametsteiner & Simula, 2003)	Complex relationship between food and forests. On positive side, many millions of households rely on nutrients sourced from forests (Nasi, Taber, & Van Vliet, 2011; Rowland et al., 2017; Wunder et al., 2014). On negative side, forest conservation can compete with food production, raising prices (P. Smith et al., 2013). Also proximity of forest to cropland can increase crop raiding by wild animals (Few et al., 2017)	Forests in the United States removed 17.4 million tonnes (t) of air pollution in 2010 with human health effects valued at 6.8 billion U.S. dollars (range: $1.5–13.0 billion) (Nowak et al., 2014)	N/A	Women face challenges in sustainable forest management (Mwangi, Meinzen-Dick, & Sun, 2011) but unclear how SFM affects gender equity.	Trees recharge atmospheric moisture, contributing to rainfall locally and in distant location, and microbial flora and biogenic VOCs associated with some trees can directly promote rainfall (Arneth et al., 2010; Ellison et al., 2017) Trees enhance soil infiltration and, under suitable conditions, improve groundwater recharge (Calder, 2007; Ellison et al., 2017; Neary et al., 2009). Many SFM practices are explicitly aimed at water supply improvement (Creed et al., 2011)	SFM may increase availability of biomass for energy (Kraxner et al., 2013; Sikkema et al., 2014)	Forest management often require employment for active replanting, etc. (Ros-Tonen et al., 2008)	SFM can increase the supply of wood for industrial use (Gustavsson & Sathre, 2011)	A few case studies show that SFM does have potential to reduce income inequality (Nhim, Lee & Phin, 2018) or historical injustices (Schelhas et al. 2017) but needs to be well-designed with community input (Faggin, Behagel & Arts 2017)	N/A	Improved forest management contributes to sustainable production goals, e.g. thru certification of timber (Rametsteiner & Simula, 2003).	Better forest management can increase adaptation benefits for millions of people (CRED 2015; World Bank et al. 2009). Also see Table SM 1, regulation of climate, for mitigation benefits.	Some acidification reduction potential, but covered in table S1. Other ocean impacts unknown	SFM aims to retain substantial levels of biodiversity, carbon, and timber stocks, e.g. through selective logging (Putz et al., 2012). SFM practices often aim at improving ecosystem functionality (Führer, 2000), and reducing degradation (see Table 1)	Sustainable forest managemen t often requires collective action institutions (Ros-Tonen et al., 2008) and community forest managemen t can contribute to stronger communitie s (Pagdee, Kim, & Daugherty, 2006)	SFM can contribute to increases in demand for wood products (e.g. certification) thereby increasing trade (McDonald & Lane, 2004)
Forestr y	**Reduced deforestation and degradation**	REDD may contribute to poverty reduction but conflicting data. Although poverty is a focus of many REDD+ projects (Arhin, 2014) evidence	Complex relationship between food and forests. On positive side, many millions of households rely on nutrients sourced from forests (Rowland et al.,	Reduced deforestation can enhance human well-being by microclimatic regulation for protecting people from heat stresses (Locatelli,	N/A	Unclear how avoided deforestation might enhance gender equity, but REDD+ projects need to pay attention to gender issues to be	Water supply is a presumed benefit of REDD programs, but unclrea evidence yet that existing REDD has increased water supply	Avoiding deforestatio n can take biofuel land out of production as they both tend to compete for land (P. Dixon, van	Reduced forest exploitation may decrease GDP and thus needs to be compensated for (e.g. through REDD+ financial	May reduce timber available for industry (Sunderlin et al., 2014)	Deforestatio n can increase inequity (Gibson 2018), but REDD+ has been shown to have no impact on inequality	N/A	N/A	Well managed REDD could have adaptation benefits for up to 25 million people (CRED 2015; World Bank et al. 2009), but few REDD plans are explicit about	Some acidification reduction potential, but covered in table S1. Other ocean impacts unknown	Reduced deforestation can enhance connectivity between forest areas and conserve biodiversity hotspots, but there are major	REDD will likely be more successful with collective institutions and may incentivize collective action	Likely to contribute to decline in trade in forest products, but increases in partnerships between donors and

		is thin that poverty reduction has actually happened (Corbera, Hunsberger, & Vaddhanaphuti, 2017; Pokorny, Scholz, & de Jong, 2013; Scheba, 2018) and in some cases benefits have been captured by wealthier participants. Opportunity costs of participation can be high (Luttrell et al., 2018)	2017), therefore REDD has potential to benefit if not in competition for cropland production and there are compensation for any losses of production (Luttrell et al., 2018)	Pavageau, et al., 2015). Trends of forest resources of nations are found to positively correlate with UNDP Human Development Index (Kauppi, Sandström, & Lipponen, 2018)		successful (Westholm & Arora-Jonsson, 2015)	access or quality for users at sites of implementation (Sunderlin et al., 2014)	Meijl, Rimmer, Shutes, & Tabeau, 2016)	transfers) (Combes Motel, Pirard, & Combes, 2009)		(Shrestha, Shrestha, & Bawa, 2017) or to increase inequality in some project areas (K. P. Andersson et al., 2018; Pelletier, Horning, Laporte, Samndong, & Goetz, 2018)			adaptation benefits (McElwee et al., 2017). Also see Table SM1, regulation of climate, for mitigation potentials		argument in literature if REDD+ mechanism sufficiently prioritizes biodiversity over carbon (Gardner et al., 2012; Panfil & Harvey, 2016) thus lesser benefits may only be realized if not well-planned (See Table SM 1)	(Saeed, McDermott, & Boyd, 2017); more evidence needed however for conclusive strong relationship	countries with REDD+ (Combes Motel et al., 2009)
	Reforestation and forest restoration	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, Swallow, & Kerr, 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., 2014; Kreidenweis et al., 2016; Reilly et al., 2012).	Reforestation can enhance human well-being by microclimatic regulation for protecting people from heat stresses (Locatelli, Catterall, et al., 2015) and remove air pollutants (Nowak et al., 2014)	N/A	Reforestation has potential for negative impact on gender if women's lands are reforested without their involvement (McElwee, 2009), and projects often focus solely on men (Lazos-Chavero et al., 2016)	Literature is mixed on reforestation and restoration impacts on water flow. 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). However, reforestation also can have adverse side-effects for reduction of water yield and water availability, dependent on species and	Reforestation can increase availability of biomass for energy (Swisher, 1994)	Reforestation often require employment for active replanting, etc (Jindal et al., 2008)	Will likely increase availability of timber for industry (Dwivedi, Khanna, Sharma, & Susaeta, 2016)	Unclear impact on equity; deforestation can increase inequity (Gibson 2018), but some reforestation projects have increased inequality due to capture of benefits by richer households (McElwee, 2009)	Urban reforestation has strong positive benefits for sustainable cities (Pincetl et al., 2013)	N/A	Could have adaptation benefits for more than 25 million people, if well managed (Griscom et al 2017). Also see Table SM1, regulation of climate, for mitigation benefits.	Some acidification reduction potential, but covered in table S1. Other ocean impacts unknown	Forest landscape restoration specifically aims to regain ecological integrity in deforested or degraded forest landscape (Maginnis & Jackson, 2007; Stanturf, Palik, Williams, Dumroese, & Madsen, 2014) However, reforestation with non-native species do not provide same biodiversity benefits (Brundu & Richardson, 2016; Hulvey et al., 2013) Animal use of restored landscapes for habitat depends on the sensitivity individual species to forest degradation (Budiharta et al., 2014) (See table 1)	N/A	N/A

							scale (Calder, 2007; Filoso et al., 2017)											
	Afforestation	Although some have argued that afforestation can be a tool for poverty reduction (Holden, Benin, Shiferaw, & Pender, 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, Catterall, et al., 2015). 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., 2014; Kreidenweis et al., 2016; Reilly et al., 2012) particularly under higher future carbon prices (Kreidenweis et al., 2016)	Afforestation can enhance human well-being by microclimatic regulation for protecting people from heat stresses (Locatelli, Catterall, et al., 2015) and remove air pollutants (Nowak et al., 2014)	N/A	Afforestation has potential for negative impact on gender if women's lands are reforested without their involvement (McElwee, 2009), and projects often focus solely on men (Lazos-Chavero et al., 2016)	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; Trabucco et al., 2008) and aggravate groundwater decline (Lu, Zhao, Shi, & Cao, 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)	Afforestation likely to increase availability of biomass for energy use, although not always clear what 'clean energy' from biomass is, given particulate emissions (Obersteiner et al., 2006)	Afforestation often requires employment for active replanting, etc. (Mather & Murray, 1987)	Will likely increase availability of timber for industry (Dwivedi et al., 2016)	Unclear impact on equity; some afforestation projects have increased inequality due to capture of benefits by richer households (McElwee, 2009) and other exclusions (Ashraf, 2019; Zinda & Zhang 2019) but other community-based projects can have more shared benefits (Andersson & Agrawal 2011)	Urban afforestation has positive benefits for sustainable cities and urban households (Pincetl et al., 2013; Sartori et al, 2019)	N/A	Adaptation benefits are dependent on type of trees planted, scale, and prior land use (Locatelli, Catterall, et al., 2015) Also see Table SM1, regulation of climate, for mitigation benefits	Some acidification reduction potential, but covered in table S1. Other ocean impacts unknown	Afforestation alone is not sufficient to increase abundance of indigenous species and habitat, as depends on type of vegetation, scale of the land transition, and time required for a population to establish (Barry, Yao, Harrison, Paragahawewa, & Pannell, 2014). Monocrop plantations on native ecosystems are bad for habitat. Some soil and land degradation benefits particularly around afforestation with use of native species (See Table SM 1)	N/A	N/A
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 (Kassie, Jaleta, Shiferaw, Mmbando, & Mekuria, 2013; Wollni, Lee, & Thies, 2010)	Increasing the SOC pool raises food productivity rates (Frank et al., 2017)	There is evidence that increasing soil organic carbon could be effective in reducing the prevalence of disease-causing helminths (Rattan Lal, 2016; Wall, Nielsen, & Six, 2015). Also indirectly contributes to food productivity which may have impact on diets.	N/A	Gender impacts use of soil organic matter practices, eg. women can be time constrained or lack information to implement (Quansah, Drechsel, Yirenkyi, & Asante-Mensah, 2001; Zhang et al., 2019) but not clear how the relationship works in reverse.	Soil organic matter is known to increase water filtration and protects water quality (Lehmann & Kleber, 2015)	N/A	Increases agricultural production generally (R Lal, 2006), therefore contributes to increased economic growth	N/A	N/A	N/A	Improved conservation agriculture contributes to sustainable production goals (Hobbs et al., 2008)	Increasing soil organic matter content reverses land degradation and provides adaptation benefits to a potential of billions of people (IPBES, 2018). Also see Table SM1, regulation of climate, for mitigation benefits	Rivers transport dissolved organic matter to oceans (Hedges et al 1997), but unclear if improved SOM will impact this and by how much. Some acidification reduction potential, but covered in table S1.	Improving soil carbon can increase overall land productivity and (more indirectly) contribute to habitat maintenance (Tscharntke et al., 2005); practices that increase soil carbon also likely benefit soil biodiversity (Bender et al., 2016) (See Table SM 1)	N/A	N/A

	Reduced soil erosion	Can increase yields for smallholders and contributes to poverty reduction (Ananda & Herath, 2003)	Contributes to increased 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	Women may be constrained in use of soil conserving practices (Zhang et al., 2019), but not clear how the relationship works in reverse.	Managing soil erosion generally improves water quality (Issaka & Ashraf, 2017)	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	Improves the resilience of agriculture to climate change and increases food production (IPBES, 2018; R. Lal, 1998).	Some acidification reduction potential, but covered in table S1. Other ocean impacts unknown	Mostly indirect: Managing for soil erosion indirectly decreases need for expanded cropland into natural habitats (Pimentel et al., 1995). Generally improves land degradation overall (See Table SM 1)	N/A	N/A
	Reduced soil salinisation	Salinisation can impoverish farmers (Duraiappah, 1998) therefore preventing or reversing can increases yields for smallholders and contribute to poverty reduction.	Reversing degradation contributes to increased food productivity and reduces food insecurity (Pimentel 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, Speldewinde, Carver, & Weinstein, 2007)	N/A	Women may be constrained in use of soil conserving practices (Zhang et al., 2019), but not clear how the relationship works in reverse.	Management of soil salinity strongly 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	Practices associated with management of groundwater, irrigation techniques, drainage, mulching and vegetation to reduce salinization also have adaptation benefits (Qadir et al. 2013; UNCTAD 2011; Dagar et al. 2016)	N/A	Soil salinization (eg. downriver from irrigation/ dams) negatively impacts ecosystem functioning, soil biodiversity, and can increase susceptibility to invasive species (Nilsson & Berggren, 2000) See Table SM 1	N/A	N/A
	Reduced soil compaction	Soil compaction and other forms of degradation can impoverish farmers (Scherr, 2000) prevention of compaction thus contributes to poverty reduction.	Compaction reduces agricultural productivity and thus contributes to food insecurity (Nawaz et al., 2013)	Soil compaction has indirect human health consequences as it contributes to runoff of water and pollutants into surface and groundwaters (Soane & Van Ouwerkerk, 1994)	N/A	Women may be constrained in use of soil conserving practices (Zhang et al., 2019), but not clear how the relationship works in reverse.	Management of soil compaction improves water quality and quantity (Soane & Van Ouwerkerk, 1994; Zalidis et al., 2002)	N/A	N/A	N/A	N/A	N/A	N/A	Will achieve adaptation benefits related to better hydrological soil functioning (Chamen, Moxey, Towers, Balana, & Hallett, 2015)	N/A	See Table SM 1, habitat creation	N/A	N/A
	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	Could potentially affect crop production if competition for land occurs (Ennis, Evans, Islam, Ralebitso-Senior, & Senior, 2012), although could also increase yields which	Biochar production could have negative health impacts from particulate matter, if low-efficiency traditional kilns used	N/A	Women may be constrained in use of soil conserving practices (Zhang et al., 2019), but not clear how the relationship works in reverse. No specific	Biochar improves soil water filtration and retention (Ennis et al., 2012; Spokas et al., 2012)	N/A	N/A	N/A	N/A	N/A	N/A	Adaptation benefits primarily related to improving the resilience of crop production systems to future climate change by increasing yield (Jeffery et al., 2017). Also see Table SM1	Some acidification reduction potential, but covered in table SM1. Other ocean impacts unknown	Biochar feedstock production could compete with natural habitat, depending on feedstock used and location of production (Meyer, Glaser &	N/A	N/A

		have shown poverty reduction benefits (Leach, Fairhead, & Fraser, 2012)	would have food security benefit (Jeffery et al., 2017)	(Sparrevik et al., 2012)		references available on biochar in particular.								for mitigation benefits		Quicker, 2011)		
	Fire management	Reducing fire destruction could have poverty impact but little lit on relationship	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 & Stephens, 2009; Winter & Fried, 2000) therefore management will reduce risk to urban areas.	N/A	Millions potentially exposure to wildfire in future without better fire management as an adaptation option (Doerr et al. (2016). Some mitigation benefits (Table SM1)	Some acidification reduction potential, but covered in table S1. Other ocean impacts unknown	Proactive fire management can improve and preserve natural habitat (Burrows, 2008) and reduce land degradation generally (see Table SM1)	N/A	N/A
	Reduced landslides and natural hazards	Landslides can increase vulnerability to poverty (Msilimba, 2010) therefore management can 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 and injury risks (Haines, Kovats, Campbell-Lendrum, & Corvalan, 2006)	N/A	N/A	Likely relationship with access to water, but little lit	N/A	N/A	N/A	N/A	Landslide hazards are a major risk to urban areas (Smyth & Royle, 2000)	N/A	Adaptation benefits from use of increasing plant cover and engineering practices as in mountainous and sloped hilly areas (Arnáez J et al. 2015; Gariano and Guzzetti 2016), little mitigation benefit	N/A	Fewer landslides can preserve natural habitat (Dolidon, Hofer, Jansky, & Sidle, 2009) and decrease land degradation generally (see Table SM 1)	N/A	N/A
	Reduced pollution including acidification	N/A	N/A	Reducing acid deposition reduces health risks, including respiratory illnesses and increased morbidity (Larssen et al., 1999; Lübkert-Alcamo & Krzyzanowski, 1995)	N/A	N/A	Pollution increases acidity of surface water, with likely ecological effects (Larssen et al., 1999); less known about access to clean drinking water by people	N/A	N/A	Management of pollution can increase demand for new technologies (D. Popp, 2006)	N/A	Management of pollution can reduced exposure to health risks in urban areas (Bartone, 1991)	N/A	Some mitigation benefits, as N depostion affects C uptake (Bala, Devaraju, Chaturvedi, Caldeira, & Nemani, 2013; Shindell et al., 2012). (See Table SM1) Unclear adaptation benefits	Reduction in pollution can improve water quality running to oceans (Doney et al., 2007). Some acidification reduction potential, but covered in Table SM1.	Air pollution like acid rain has major impacts on habitats like lakes (Schindler, Kasian, & Hesslein, 1989); see Table SM1	N/A	N/A
Other eco-system manag ement	**Management of invasive species / encroachment**	Invasive species removal policies can be 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 increase employment due to need for labour (Van Wilgen & Wannenburgh, 2016)	N/A	N/A	N/A	N/A	Adaptation benefits from increased resilience of ecosystems to climate change (Mainka & Howard, 2010; Reaser et al., 2007)	N/A	Many invasive alien species (IAS) diminish biodiversity; improved management of IAS can lead to improved habitat and ecosystems (Richardson & Wilgen, 2004) (See Table SM 1)	N/A	N/A

	Restoration and avoided conversion of coastal wetlands	Nearly 100 million people rely on coastal systems for livelihoods (Hinkel et al. 2014). But impacts on poverty are mixed (Kumar et al., 2011). May reduce land available for food production, and poor design of interventions can impoverish people (J. C. Ingram, Franco, Rio, & Khazai, 2006; Mangora, 2011)	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)	Mixed evidence; wetland conservation can increase mosquito presence and disease, but wetlands important for clean water filtration for human health as well (Dale & Connelly, 2012; Horwitz & Finlayson, 2011)	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, Hole, & Zavaleta, 2012) and replace with Nature-based solutions, which could have positive econ impact for some industries	N/A	N/A	N/A	Improved wetland management is adaptation strategy that can decrease vulnerability to coastal storms (Feagin et al., 2010; H. P. Jones et al., 2012). Also mitigation benefits (See Table SM1)	Restoration of coastal wetlands can play a large role in providing habitat for marine fish species (Bobbink et al., 2006; Hale et al., 2009)	Coastal wetlands are important natural habitats (Griscom et al., 2017; J. Howard et al., 2017)	N/A	N/A
	Restoration and avoided conversion of peatlands	May reduce land available for smallholders in tropical peatlands and could increase poverty (Jewitt et al., 2014; Senaratna Sellamuttu, de Silva, & Nguyen-Khoa, 2011)	Can reduce crop production, e.g. use of peatlands in tropics for palm oil and other food crops (Senaratna Sellamuttu et al., 2011)	Positive health benefits from reduced burning of peatlands in tropics, which produces haze (Tacconi, 2016)	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., 2009)	Reduced peatland exploitation may decrease GDP in Southeast Asia (Koh, Miettinen, Liew, & Ghazoul, 2011)	N/A	N/A	N/A	N/A	Unknown adaptation benefits. Some mitigation benefits (see Table SM1).	Some acidification reduction potential, but covered in table SM1. Other ocean impacts unknown	Peatlands are important natural habitats (Lindsay, 1993)	N/A	N/A
	Biodiversity conservation	There is mixed evidence on the impacts of biodiversity conservation measures on poverty e.g protected areas. There is congruence between high poverty and high biodiversity but the exact nature of relationship is contested (W. M. Adams, 2004; Barrett, Travis, & Dasgupta, 2011; Fisher & Christopher, 2007)	Biodiversity conservation can improve sustainable and diversified diets (Global Panel on Agriculture and Food Systems for Nutrition, 2016). However, at the same time, some options to preserve biodiversity, like protected areas, may potentially conflict with food production by local communities (Molotoks, Kuhnert, Dawson, & Smith, 2017)	Biodiversity is crucial for improving sustainable and diversified diets (Global Panel on Agriculture and Food Systems for Nutrition, 2016). Indirectly, the loss of pollinators would contribute to 1.42 million additional deaths per year from non-communicable and malnutrition-related diseases, and 27.0 million lost disability-	N/A	Mixed evidence: women play important roles in biodiversity conservation due to gendered use of the environment (Momsen, 2007; Rocheleau, 1995) but women are often excluded for management institutions (Bandiaky, 2008)	Biodiversity conservation measures such as protected areas can help ensure water supplies (Secretariat of the Convention on Biological Diversity, 2008)	Some biodiversity conservation measures might increase access to biomass supplies (Erb, Haberl, & Plutzar, 2012) while others might restrict them; context dependent	Economic benefits are very context dependent; positive economic benefits from protected areas and conservation measures (e.g. ecotourism) in many places (Smis 2010; Balmford et al. 2015), while some local lost income from restrictions on land use are common (McElwee 2010). Economic impacts of marine protected areas tend to show long-	Protected areas can be off-limits for development of industry (e.g. mining, oil exploration)	Studies show existing inequality affects policies for protected areas (Kashwan 2017); likely a relationship in reverse (between location of protected areas and inequality) but no clear lit. Plans to expand conservation to half the planet have been criticized for equity implications (Buscher et al. 2017)	33 out of 105 of the largest urban areas worldwide rely on biodiversity conservation measures such as protected areas for some, or all, of their drinking water (Secretariat of the Convention on Biological Diversity, 2008)		Likely strong adaptation benefits for millions who depend on biodiversity for livelihoods (Munang, Andrews, Alverson, & Mebratu, 2014); also, mitigation benefits (see Table SM1)	Biodiversity conservation measures like protected areas can increase ocean biodiversity (Selig et al., 2014); also some acidification benefits from mitigation	Biodiversity conservation includes measures aiming to promote species richness and natural habitats e.g. protected areas (Powers & Jetz, 2019) See Table SM 1	Some measures for biodiversity conservation e.g. peace parks, transboundary protected areas, indigenous territories, can reduce conflict (Hanks, 2003; King & Wilcox, 2008)	Transboundary biodiversity conservation can increase partnerships, but may reduce trade due to restrictions on use of flora and fauna (Abensperg-Traun, 2009)

				adjusted life-years per year (MR Smith et al., 2015).					term positive benefits (Lynam et al. 2020) but some short term losses in some cases (Dalton 2004)									
CDR	**Enhanced weathering of minerals**	N/A	N/A	N/A	N/A	N/A	Mineral weathering can negatively affect the chemical composition of soil and surface waters (Katz, 1989; Atekwana, Atekwana, Legall, & Krishnamurthy, 2005)	N/A	N/A	Will require development of new technologies (Schuiling & Krijgsman, 2006)	N/A	N/A	N/A	Unknown adaptation benefits; some moderate mitigation benefits (Table SM1)	N/A	N/A	N/A	N/A
CDR	**Bioenergy and BECCS**	Bioenergy production could create jobs but could also compete for land with alternative uses (Humpenöder et al., 2018; Smith, Davis, et al., 2016; Clarke et al., 2014; Popp et al., 2017). Therefore, bioenergy could have positive or negative effects on poverty rates among smallholders, among other social effects (Dooley & Kartha, 2018; IPCC, 2018).	Biofuel plantations may lead to decreased food security through competition for land. Large scale deployment of bioenergy and BECCS can lead to significant trade-offs with food production (Humpenöder et al., 2018; Popp, Lotze-Campen, et al., 2011; Smith, Haszeldine, & Smith, 2016; IPCC, 2018)	BECCS could have positive effects through improvements in air quality (IPCC, 2018) but bioenergy and BECCS could have negative effects on health and wellbeing through impacts on food systems and water (Burns & Nicholson, 2017; Humpenöder et al., 2018)	N/A	N/A	Depending on the feedstock, can require water. Models show high risk of water scarcity if BECCS is deployed on widespread scale (Hejazi et al., 2014; Popp, Dietrich, et al., 2011; Smith et al., 2016) through both increases in water withdrawals (Bonsch et al., 2015; Hejazi et al., 2014; IPCC, 2018) and changes in surface runoff (Cibin, Trybula, Chaubey, Brouder, & Volenec, 2016)	Bioenergy and BECCS can contribute up to 300 EJ of primary energy by 2100 (Clarke et al., 2014); bioenergy can provide clean, affordable energy (IPCC, 2018)	Access to clean, affordable energy will help economic growth (IPCC, 2018)	BECCS will require development of new technologies (Smith, Haszeldine, & Smith, 2016)	N/A	N/A	Switching to bioenergy reduces depletion of finite resources (IPCC, 2018)	Large mitigation potential depending on scale e.g. up to ~11 $GtCO_2\ yr^{-1}$ (IPCC, 2018; Smith et al., 2020), but potentially large negative adaptation effects due to land competition (Dooley & Kartha, 2018; Fuss et al., 2016; Humpenöder et al., 2018).	Bioenergy and BECCS will reduce ocean acidification (covered in Table 1) but unknown other effects on oceans	Can reduce areas of natural habitat with negative effects on biodiversity (Hof et al., 2018; Immerzeel et al., 2014; IPCC, 2018)	N/A	N/A

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

Integrated response options based on value		**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**

chain management																		
	Dietary change	Reduced demand for livestock may have negative effect on pastoralists and could suppress demand for other inputs (grains) that would affect poor farmers (Garnett, 2011; Roy et al., 2018) ; could be made up with demand for other products but little lit	Reduced meat consumption can free up land for other activities to increase food production (Röös et al., 2017; Stoll-Kleemann & O'Riordan, 2015). High-meat diets in developed countries may limit improvement in food security in developing countries (Rosegrant, Leach, & Gerpacio, 1999); dietary change can contribute to food security goals (Bajželj et al., 2014; Godfray et al., 2010)	Overnutrition contributes to worse health outcomes, including diabetes and obesity (A. J. McMichael, Powles, Butler, & Uauy, 2007; Tilman & Clark, 2014). Dietary change away from meat consumption has major health benefits, including reduced heart disease and mortality (Friel, Marmot, McMichael, Kjellstrom, & Vågerö, 2008; Popkin, 2008). Dietary change could contribute to 5.1 million avoided deaths per year (Springmann et al., 2016)	N/A	N/A	Reduced meat consumption will reduce water consumption. (Muller et al., 2017) found that dietary change and waste reduction would lead to decreases in use of fertiliser (nitrogen and phosphorus), pesticides, water and energy. However, Tom et al. (2016) found water footprints of fruit/veg dietary shift in the US to increase by 16%	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 local urban food systems (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 (Bajželj et al., 2014; Stehfest et al., 2009).	Unknown adaptation benefits; high mitigation benefits (Table SM1)	Dietary change away from meat might put increased pressure on fish stocks (Mathijs, 2015; Vranken, Avermaete, Petalios, & Mathijs, 2014). Some acidification reduction potential, but covered in table SM1.	Can lead to reduced expansion of agricultural lands, which can spare/increase natural habitat (Tilman et al., 2001; Laroche et al., 2020)	N/A	N/A
Demand management	**Reduced post-harvest losses**	Reducing food losses from storage and distribution operation can increase economic well-being without additional investment in production activities, which is beneficial to poor (Bradford et al., 2018)	Reducing food losses increases food availability, nutrition, and lower prices (Abass et al., 2014; Affognon, Mutungi, Sanginga, & Borgemeister, 2015; Sheahan & Barrett, 2017)	Improved storage enhances food quality and can reduce mycotoxin intake (Bradford et al., 2018; Stathers et al., 2013; Temba et al., 2016; Tirado, Clarke, Jaykus, McQuatters-Gollop, & Frank, 2010) especially in humid climates. The perishability and safety of fresh foods are highly susceptible to	Reduced losses can increase income that could be spent on education, but no data available	Postharvest losses do have a gender dimension (Kaminski & Christiaensen, 2014), but unclear if reducing losses will contribute to gender equality (Rugumamu, 2009)	(Kummu et al., 2012) report 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 & 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, Buzby, & Bennett, 2011)	Reducing PHL can involve improving infrastructure for farmers and marketers (Parfitt, Barthel, & Macnaughton, 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)	Adaptation benefits for over 250 million people due to increased availability of food (Kummu et al. 2012). Also mitigation benefits (See Table SM1)	Some acidification reduction potential, but covered in table SM1.	Will lead to reduced expansion of ag lands, which can preserve natural habitat (Tilman et al., 2001), although not well quantified in lit for post-harvest losses specifically	N/A	Post harvest losses contribute to higher food prices and constraints on trade (Tefera, 2012)

				temperature increase (Bisbis, Gruda, & Blanke, 2018; J Ingram et al., 2016).														
	Reduced food waste (consumer or retailer)	Food waste tends to rise as incomes rise (Junguo Liu, Lundqvist, Weinberg, & Gustafsson, 2013; Parfitt et al., 2010), so it is not clear what the relationship to poverty is. Redistribution of food surplus to the poor could also have impacts on poverty (Papargyropoulou, Lozano, K. Steinberger, Wright, & Ujang, 2014)	People who are already food insecure tend not to waste food (Nahman, de Lange, Oelofse, & Godfrey, 2012). Reduced food waste would increase the supply of food (FAO, 2011; P. Smith & Gregory, 2013) but it is unclear if this would benefit those who are food insecure in developing countries (Hertel & Baldos, 2016).	Food waste can increase with healthier diets (Parizeau, von Massow, & Martin, 2015). Health and safety standards can restrict some approaches to reducing food waste (Halloran, Clement, Kornum, Bucatariu, & Magid, 2014). Changes in packaging to reduce waste might have negative health impacts (e.g. increased contamination) (Claudio, 2012)	Could be potentially beneficial as it would free up money to spend on other activities (Dorward, 2012) but unclear role of education	Reducing food waste within households often falls to women (Stefan, van Herpen, Tudoran, & Lähteenmäki, 2013) and can increase their labour workload (Hebrok & Boks, 2017). Women also generate more food waste and could be a site for intervention (Thyberg & Tonjes, 2016)	(Kummu et al., 2012) report 24% of global freshwater use and 23% of global fertiliser use is attributed to food losses. (Muller et al., 2017) 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.	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 & Webber, 2010). However, food waste can be a sustainable source of biofuel (Uçkun Kiran, Trzcinski, Ng, & Liu, 2014)	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 & de Lange, 2013). Reductions of postconsumer waste would increase household income (Hodges et al., 2011)	N/A	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 (J. Smit & Nasr, 1992; Zaman & 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.	Un-quantified adaptation benefits; see Table SM1, regulation of climate, for mitigation benefits	Reducing food waste may be related to food packaging, which is a major source of ocean pollution (Hoornweg, Bhada-Tata, & Kennedy, 2013; Lebreton et al., 2017); Some acidification reduction potential, but covered in table SM1	Improved storage and distribution reduces food waste and the need for compensatory intensification of agricultural areas (land sparing) and land use change (Stathers, Lamboll, & Mvumi, 2013)	N/A	Food waste can contribute to higher food prices and constraints on trade (Tefera, 2012)
	Material substitution	N/A	Could increase demand for wood and compete with land for agriculture (Petersen & Solberg, 2005)	N/A	N/A	N/A	If water is used efficiently in production of wood, likely to be positive impact over cement production (Gustavsson & Sathre, 2011)	Concrete frames require 60-80% more energy than wood (Börjesson & Gustavsson, 2000). Material substitution can reduce embodied energy of buildings construction by up to 20% (Thormark, 2006; Upton, Miner, Spinney, & Heath, 2008)	The relationship between material substitution and GDP growth is unclear (Moore, Tilton, & Shields, 1996)	Material substitution may reduce need for industrial production of cement etc. (Petersen & Solberg, 2005)	N/A	Changing materials for urban construction can reduce cities' ecological footprint (Zaman & Lehmann, 2013)	Material substitution is a form of sustainable production/consumption which replaces cement and other energy-intensive materials with wood (Fiksel, 2006)	Unknown adaptation benefits; some mitigation benefits (see Table SM1)	N/A	Material substitution increases demand for wood, which can lead to loss of habitat (Sathre & Gustavsson, 2006)	N/A	N/A
Supply management	**Sustainable sourcing**	Value adding and sustainable sourcing has been promoted as a poverty reduction strategy (Lundy et al. 2002; Whitfield 2012). Poor farmers can benefit from value-adding	Sustainable sourcing may help to improve food security by increasing economic performance and revenues to local farmers through higher prices	Sustainable sourcing and improved value-chains could help increase the nutritional status of food reaching consumers	Value-adding can increase income that could be spent on education, but no data available	Women are highly employed in sustainable sourcing in many developing countries, but do not always gain	Possible benefits due to improved ecosystem management but no literature specifically on water	N/A	Sustainable sourcing can expand markets and generate additional employment and expands GDP in developing	Sustainable sourcing can create incentives to improve infrastructure in processing (Delgado, 1999). Expanding value chains can incorporate new	Data shows high-value agriculture is not always a pathway toward enhanced welfare (Dolan & Sorby, 2003;	Sustainable souring can increase incentives to keep peri-urban agriculture, but faces threats from rising land prices in urban	Value-adding in agriculture (e.g. fair trade, organic) can be an important source of sustainable consumption and	Likely some adaptation benefits due to increased incomes (Tayleur et al. 2018); unquantified mitigation	Fisheries certification can have positive impact on ocean ecosystems (Jacquet et al. 2010), although	Commodity production is responsible for nearly 40% of deforestation (Henders, Persson, & Kastner, 2015). Forest	Many certification/ sourcing programs have community institutional	Value-adding has a strong relationship to expanding trade in developing countries in particular (Newfarmer et al., 2009)

		and new markets (Bamman, 2007; Swanson, 2006). However, much value-adding is captured upstream, not by poor producers so overall benefits uncertain (McMichael & Schneider, 2011; Oya, Schaefer &Skalidou 2018), and much sustainable sourcing is not directed to the poorest areas globally, so promise is not yet being met (Tayleur et al. 2018).	(Reidsma, Ewert, Lansink, & Leemans, 2010); however, one study found increased food insecurity among indigenous peoples near a forest certification site (Doremus 2019), so likely depends on what is being certified/sourced	(e.g. organic standards) (Fan & Pandya-Lorch, 2012)		substantive benefits (Dolan & Sorby, 2003). Value-chains that target women could increase gender equity, but data is scare (Gengenbach, Schurman, Bassett, Munro, & Moseley, 2018)			countries in particular (Newfarmer, Shaw, & Walkenhorst, 2009)	sources of food producers into industrial systems of distribution (Bloom & Hinrichs, 2011)	Oya et al. 2018), and much value-adding is captured not by smallholders but higher up the chain (Neilson, 2007), which could create inequality	areas (Midmore & Jansen, 2003)	production (De Haen & Réquillart, 2014); however,	benefits but possible.	evidence is somewhat mixed (Ward 2008). Some acidification reduction potential, but covered in table SM1	certification and other sustainable sourcing schemes can reduce habitat fragmentati on as compared to conventiona l supply chains (Rueda, Thomas, & Lambin, 2015; Tayleur et al. 2018))	building as an explicit goal (Sirdley & Lallau, 2020)	
	Manage-ment of supply chains	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 & Martin, 2008) to 450 million people (Brinkman, De Pee, Sanogo, Subran, & Bloem, 2009), and caused welfare losses of 3% or more for poor households. Better management would have positive poverty impacts.	Food insecure consumers benefit from better access and distribution (Coveney & O'Dwyer, 2009; John Ingram, 2011) Food prices strongly affect food security (Fujimori et al., 2019; Lewis & Witham, 2012; Regmi & Meade, 2013), and policies to improve supply chains will likely have strong impacts on food security (Raleigh, Choi, & Kniveton, 2015; Timmer, 2009; Torlesse, Kiess, & Bloem, 2003).	Access to quality food is a major contributor to whether a diet is healthy or not (Neff, Palmer, McKenzie, & Lawrence, 2009) and better supply chains may increase access	N/A	Women and girls are often the most effected ones in households when there are food shortages, therefore increased access likely benefits them (Hadley, Lindstrom, Tessema, & Belachew, 2008; Kerr, 2005)	Increasing food imports can contribute to water scarcity through "embodied" or "virtual" water accounting (Guan & Hubacek, 2007; Hanjra & Qureshi, 2010; Jiang, 2009; Yang & Zehnder, 2002)	Food supply chains and flows can have adverse effects due to reliance on non-renewable energy for long-distance shipping (Kurian, 2017; A. Scott, 2017).	Better supply chain management can reduce price volatility, which can contribute to consumer price inflation and higher import costs as a percentage of GDP leading to account deficits (Gilbert & Morgan, 2010)	Excessive disruptions in food supply can place strains on infrastructure (e.g. needing additional storage facilities) (Yang & Zehnder, 2002). Improved food transport can create demands for improved infrastructure (Akkerman, Farahani, & Grunow, 2010; Shively & Thapa, 2016).	Improved food distribution could reduce inequality in access to high quality nutritious foods (Baldos & Hertel, 2015; Frank et al., 2017; Porter et al., 2014; Wheeler & von Braun, 2013).	Improved food distribution can contribute to better food access and stronger urban communities (Hendrickson, Smith, & Eikenberry, 2006; Kantor, 2001). Food price spikes often hit urban consumers the hardest in food importing countries, and increasing stability can reduce risk of food riots (Cohen & Garrett, 2010).	Improved storage and distribution are likely to contribute to sustainable production (J Ingram et al., 2016).	Likely medium to large adaptation benefits due to improved access to food storage and distribution especially in countries with inadequate infrastructure (Vermeulen, Campbell, et al., 2012) can strengthen climate resilience against future climate-related shocks (J Ingram et al., 2016; Stathers et al., 2013)	N/A	N/A	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 & Hertel, 2015; Frank et al., 2017; Porter et al., 2014; Wheeler & von Braun, 2013).
	Enhanced urban food systems	As urban poor spend a great deal of their budget on food, enhanced UFS could reduce prices and contribute to poverty reduction for urban farmers (Ellis & Sumberg, 1998).	Food insecurity in urban areas is often invisible (Crush & 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 (Benis & Ferrão, 2017; Brinkley,	Urban diets are exposed to more unhealthy 'fast foods', and enhanced urban food systems can contribute to enhanced nutrition in urban areas (J. Dixon et al., 2007; Maxwell, 1999; Neff et	School feeding programs in urban areas can increase educational attendance and outcomes (Ashe & Sonnino, 2013)	Women play an important role in the provisioning of urban food (Binns & Lynch, 1998; Tao et al., 2015). Women also dominate informal urban food provisioning (wet markets, street food)	Water access often a constraint on urban agriculture (Badami & Ramankutty, 2015; de Bon et al., 2010). Urban agriculture can exacerbate urban water pollution problems (pesticide runoff, etc)	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 (Coley,	Urban food systems have as one aim to stimulate local economic development and increase employment in urban agriculture and food processing (D. W. Smith, 1998). As many as 50% of some cities'	Urban food provisioning creates demands for expanded infrastructure in processing, refrigeration, and transportation (Pothukuchi & Kaufman, 1999)	Many UFS in global South have goals to reduce inequality in access to food. (Allen, 2010; J. Dixon et al., 2007)	Urban food systems present opportunities for resilient food supply (Brinkley et al., 2016; Rocha, 2016). through improving the health status of urban dwellers and stimulating economic development (Tao et al., 2015)	UFS aim to combine sustainable production and consumption with local foodsheds (Allen, 2010; Tao et al., 2015)	Likely strong adaptation benefits due to increased access to food that is closer and fresher and less likely to experience disruptions from climate (Tao et al., 2015).	Some urban food systems rely on aquaculture with positive health/food benefits (Bunting & Little 2015) but not clear impact on oceans	Urban gardening can improve habitat and biodiversity in cities (Lin, Philpott, & Jha, 2015; Orsini et al., 2014)	Building a resilient regional food system requires building local institutio ns (Akhtar, Tse, Khan, & Rao-Nicholso n, 2016).	N/A

			Birch, & Keating, 2016; Maxwell & Wiebe, 1999; Rocha, 2016; W. Smit, 2016), particularly in fostering regional food self-reliance (Aldababseh, Temimi, & Maghelal, 2018; Bustamante et al., 2014).	al., 2009; Tao et al., 2015).		(D. W. Smith, 1998)	(Pothukuchi & Kaufman, 1999)	Howard, & Winter, 2009; Mariola, 2008)	retail jobs are in food-related sector (Pothukuchi & Kaufman, 1999)								Production of food within cities can potentially lead to less likelihood of urban food shortages and conflicts (Cohen & Garrett, 2010)	
	Improved food processing and retailing	Food processing has been a useful strategy for poverty reduction in some countries (Haggblade, Hazell, & Reardon, 2010; Weinberger & Lumpkin, 2007)	Improving storage and processing can reduce food waste and health risks associated with poor management practices (Bradford et al., 2018; James & James, 2010; Stathers et al., 2013; Tirado et al., 2010). Improved food processing and supply chains can contribute to more food reaching consumers and improved nutrition (Keding, Schneider, & Jordan, 2013; Vermeulen, Campbell, et al., 2012; Hollis-Hansen et al 2019)	Improved processing and distribution & storage systems can provide safer and healthier food to consumers (Vermeulen, Campbell, et al., 2012) and reduce food waste and health risks associated with poor storage management practices (James & James, 2010), although overpackaged prepared foods that are less healthy are also on rise (Galal, Corroon, & Tirado, 2010; Carlos A. Monteiro, 2009; Carlos Augusto Monteiro, Levy, Claro, de Castro, & Cannon, 2011)	N/A	Improved food processing can displace street venders and informal food sellers, who are predominantly women (J. Dixon et al., 2007; D. W. Smith, 1998)	Food processing and packaging activities such as washing, heating, cooling are heavily dependent on freshwater so improved postharvest storage and distribution could reduce water demand via more efficiently performing systems (Garcia & You, 2016).	Food processing and packaging activities such as heating and cooling are heavily dependent on energy so improved efficiency could reduce energy demand (Garcia & You, 2016).	Phytosanitary barriers currently prevent much food export from developing countries, and improvements in processing would increase exports and GDP (Henson & Loader, 2001; Jongwanich, 2009).	Improvements in processing, refrigeration, and transportation will require investments in improved infrastructure (John Ingram, 2011)	Inequality in access to food could increase if food processing aimed at wealthier consumers (Ericksen, 2008)	Improved food transport can reduce cities' ecological footprints and reduce overall emissions (Du, Zhang, Song, & Wen, 2006)	Improved food processing and agro-retailing contributes to sustainable production (John Ingram, 2011)	Likely adaptation benefits in terms of better access to food and improved storage such as weatherproofing transport systems, but unquantified (World Bank, 2017)	N/A	N/A	N/A	Improved processing increases chances for expanding trade in developing countries (Newfarmer et al., 2009)
	Improved energy use in food systems	Reducing food transport costs generally helps farmers (Altman, Hart, & Jacobs, 2009) bur unclear if improved energy use will impact poverty.	There is some limited evidence that improved transport increases food security in developing countries (Hine, 1993). Utilising energy-saving	Organic agriculture is associated with increased energy efficiency, which have can have co-benefits by reduced	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 (Ringler & Lawford, 2013; Rothausen & Conway, 2011)	Increased energy efficiency will reduce demands for energy ; rebound effect is unclear (Swanton, Murphy,	There is no clear association between higher energy use in agriculture and economic growth; these have become	N/A	N/A	N/A	Reducing energy use in agriculture contributes to sustainable production goals (J Ingram et al., 2016).	Adaptation benefits due to reduced cost of energy inputs and increased food productivity, but unquantified (World Bank,	Some acidification reduction potential, but covered in table SM1	N/A	N/A	N/A

			strategies can support reduced food waste (J Ingram et al., 2016) and increased production efficiencies (P. Smith & Gregory, 2013).	exposure to agrochemicals by farm workers (Gomiero, Paoletti, & Pimentel, 2008)				Hume, & Clements, 1996).	decoupled in many countries (Bonny, 1993). Data is unclear though on economic impacts of potential cost savings but likely to be some.					2017). Also some mitigation benefits, see Table SM1,				

Table S6 Literature on Impacts on the UN SDG of integrated response options based on risk management

<u>Integrated response options based on risk 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
	Management of urban sprawl	Inner city poverty closely associated with urban sprawl in US context (Deng & Huang, 2004; Frumkin, 2002; Jargowsky, 2002; Powell, 1999)	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., 2013) Some evidence for sprawl reducing food production, particularly in China (J. Chen, 2007)	Strong association between urban sprawl and poorer health outcomes (air pollution, obesity, traffic accidents) (Freudenberg, Galea, & Vlahov, 2005; Frumkin, 2002; Lopez, 2004)	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 & 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, Gandhi, Chaurey, & Agarwal, 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 (Godschalk, 2003)	Urban sprawl often increases public infrastructure costs (Brueckner, 2000), and densification and redevelopment can improve equality of access to infrastructure (Jenks & 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 (E. Andersson, 2006; Kombe, 2005). Sustainable cities include compactness, sustainable transport, density, mixed land uses, diversity, passive solar design, and greening (E. Andersson, 2006; H. Chen, Jia, & Lau, 2008; Jabareen, 2006)	Reducing urban sprawl and promoting community gardens and periurban agriculture can contribute to more sustainable production in cities (B. Turner, 2011)	Improved quality of life could lead to enhanced resilience for potentially millions (Stone et al. 2010); mitigation benefits as well (see Table SM1)	Some acidification reduction potential, but covered in table SM1	Reducing urban sprawl can help preserve natural habitat in periurban areas (Pataki et al., 2011)	Urban sprawl may reduce social capital and weakening participatory governance in cities (Frumkin, 2002; Nguyen, 2010)	N/A
	Livelihood diversification	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).	Diversification is associated with increased access to income and additional food sources for the household (J. Pretty, 2003); likely some food security benefits	More diversified livelihoods have diversified diets which have better health outcomes (Block & Webb, 2001; Kadiyala et al., 2014) particularly for women and children (J. Pretty, 2003)	More diversified households tend to be more affluent, & have more disposal income for education (Ellis, 1998; Estudillo & Otsuka, 1999; Steward, 2007), but diversification through migration may reduce educational	Women are participants in and benefit from livelihood diversification, such as having increased control over sources of HH income (N. M. Smith, 2014) although it can increase their labour requirements	Lack of access to affordable water may inhibit livelihood diversification (Calow, MacDonald, Nicol, & Robins, 2010) but unclear if diversification increases water consumption	Access to clean energy can provide additional opportunities for livelihood diversification (Brew-Hammond, 2010; Suckall, Stringer, & Tompkins, 2015) but unclear if diversification requires more energy use	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 (R. H. Adams, 1994) while in others cases it increases it (Reardon, Taylor,	One part of urban livelihoods in developing countries are linkages between rural and urban areas through migration and remittances (C Rakodi & Lloyd-Jones, 2002; Carole Rakodi, 1999); this livelihood diversification can strengthen urban income (Ricci, 2012)	Livelihood diversification can strengthen autonomy potentially leading to better choices for consumption and production (Elmqvist & Olsson, 2007; S. Schneider & Niederle, 2010)	Livelihood diversificatation is a well acknolwedged adaptation strategy to reduce risk (Morton 2007; Rigg 2006)	N/A	Could have indirect impacts if diversification allows land sparing or reduction in land conversion, but no literature	N/A	N/A

					outcomes for children (Gioli, Khan, Bisht, & Scheffran, 2014)	(Angeles & Hill, 2009)					Stamoulis, Lanjouw, & Balisacan, 2008)							
	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, Funes-Monzote, & Petersen, 2012; Howard, 2015; McGuire & Sperling, 2016)	Local seeds revive and strengthen local food systems (McMichael & Schneider, 2011) and lead to more diverse and healthy food in areas with strong food sovereignty networks (Bisht et al., 2018; Coomes et al., 2015). However local seeds can be less productive than improved varieties.	Local seed use is associated with fewer pesticides (Altieri et al., 2012); loss of local seeds and substitution by commercial seeds is perceived by farmers to increase health risks (Mazzeo & Brenton, 2013), although overall literature on links between food sovereignty and health is weak (Jones, Shapiro, & Wilson, 2015)	N/A	Women play important roles in preserving and using local seeds (Bezner Kerr, 2013; Ngcoya & Kumarakulasingam, 2017) and sovereignty movements paying more attention to gender needs (Park, White, & Julia, 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) although exact numbers unknown	N/A	Seed sovereignty advocates believe it will contribute to reduced inequality (Park et al., 2015; Wittman, 2011) but empirical evidence limited.	Seed sovereignty can help sustainable urban gardening (Demailly & Darly, 2017) which can be part of a sustainable city by providing fresh, local food (Leitgeb, Schneider, & Vogl, 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., 2015; Van Niekerk & Wynberg, 2017).	Local seeds tend to be resilient to different climate hazards and thus can enhance adaptation (Louwaars 2002; Santilli 2012)	N/A	Use of commercial seeds can contribute to habitat loss through agricultural expansion and intensification; local seeds likely better (Upreti & Upreti, 2002)	Seed sovereignty is positively associated with strong local food movements, which contribute to social capital (Coomes et al., 2015; Grey & Patel, 2015; McMichael & Schneider, 2011).	Seed sovereignty could be seen as threat to free trade and imports of genetically modified seeds (Howard, 2015; Kloppenberg, 2010; Kloppenburg, 2014)
	Disaster risk management	DRM can help prevent impoverishment as disasters are a major factor in poverty (Basher, 2006; Fothergill & Peek, 2004)	Famine early warning systems have been successful to prevent impending food shortages and can improve food security (Genesio et al., 2011; Hillbruner & Moloney, 2012)	DRM very important for public health to ensure people can get shelter and medical care during disasters (Ebi & Schmier, 2005; Greenough et al., 2001)	Effective DRM is important to ensure continued access to schools and education during hazards (Tatebe & Mutch, 2015)	Women often disproportionately affected by disasters; gender-sensitive EWS can reduce their vulnerability (Enarson & Meyreles, 2004; Mustafa et al., 2015)	Many DRM include water monitoring components that contribute to access to clean water (Iglesias, Garrote, Flores, & Moneo, 2007; Wilhite, 2005)	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 & Tsirkunov, 2011)	DRM can reduce inequality is since poorer people tend to be more vulnerable to impacts (Khan, Mock, & Bertrand, 1992), but must be careful to avoid excluding populations	DRM can be very effective in urban settings such as heat wave and flooding early warning systems to minimise vulnerability (Bambrick, Capon, Barnett, Beaty, & Burton, 2011; Djordjević, Butler, Gourbesville, Mark, & Pasche, 2011; Parnell, Simon, & Vogel, 2007)	DRM can make sustainable production more possible by providing farmers with advance notice of environmental needs (Parr, Sier, Battarbee, Mackay, & Burgess, 2003; Stigter, Sivakumar, & Rijks, 2000)	DRM is excellent adaptation strategy reaching the largest number of people (billions) worldwide (Hillbruner and Moloney 2012)	DRM can play role in marine management, e.g. warnings of red tide, tsunami warnings for coastal communities (Lauterjung, Münch, & Rudloff, 2010; J. H. W. Lee, Hodgkiss, Wong, & Lam, 2005)	Many habitats confer disaster protection (Kousky 2010), and some DRM strategies may include habitat protection explicitly for a positive benefit (Shreve & Kelman 2014) (e.g. mangrove protection), but unclear how extensive	DRM can reduce risk of conflict (Meier, Bond, & Bond, 2007), increase resilience of communities (Mathbor, 2007) and strengthen trust in institutions (Altieri et al., 2012)	N/A

																DRM benefiting habitats is		
	Risk sharing instruments	Crop insurance reduces risks which can improve poverty outcomes by avoiding catastrophic losses, but is often not used by poorest people, who may rely on more informal risk sharing (Platteau, De Bock, & Gelade, 2017)	Availability of crop insurance has generally lead to (modest) expansions in cultivated land area and increased food production (RL Claassen et al., 2011; Goodwin et al., 2004); other risk sharing instruments are aimed at food access and provisioning.	General forms of social protection lead to better health outcomes; somewhat unclear how much formal risk sharing contributes (Tirivayi, Knowles, & Davis, 2016)	Households lacking insurance may withdraw children from school after crop shocks (Bandara, Dehejia, & Lavie-Rouse, 2015; Jacoby & Skoufias, 1997)	Women farmers vulnerable to crop shocks, but tend to be more risk-averse and skeptical of commercial insurance and rely on more informal systems (Akter, Krupnik, Rossi, & Khanam, 2016; Fletschner & Kenney, 2014)	Mixed evidence on if crop insurance encourages or reduces non-point source pollution (M. S. Bowman & Zilberman, 2013; Luo, Wang, & Qin, 2014)	N/A	Subsidised crop insurance contributes to economic growth in the US (Atwood, Watts, & Baquet, 1996) but at considerable cost to the government (Glauber, 2004).	N/A	N/A	N/A	Crop insurance has been implicated as a driver of unsustainable production and disincentive to diversification (M. S. Bowman & Zilberman, 2013) although community risk sharing might increase diversification and production	Different risk sharing instruments spread risk and increase resilience, improving adaptation for millions (Platteau et al. 2017), although they can be negative for mitigation (see Table 1, regulation of climate)	There is mixed evidence that crop insurance may encourage excess fertiliser use (Kramer, McSweeny, & Stavros, 1983; V. H. Smith & Goodwin, 1996; Wu, 1999), which contributes to ocean pollution; however, some governments re requiring reductions in nonpoint source pollution from farms otherwise farmers lose crop insurance (Iho, Ribaudo, & Hyytiäinen, 2015)	See Table SM 1, habitat creation	Community risk sharing instruments can help strengthen resilience and institutions (Agrawal, 2001)	Subsidised crop insurance can be seen as a subsidy and barrier to trade (Young & Westcott, 2000)

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