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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

Running Title: Impact of interventions in global land sector

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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 has 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 (NCP) and the 17 Sustainable Development Goals (SDG). 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 (BECCS), 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 decisionmakers choose the more effective, or at the very minimum, more benign interventions for implementation.

Key words: sustainable development, Nature's Contribution to People, ecosystem services, mitigation, adaptation, land degradation, food security, 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; IPBES, 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 (NCP), 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 NCP 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 (clear water and sanitation and life on land), while positive effects were noted on SDG 3 (good health) and SDG 7 (affordable and clean energy). However, 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 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 socio-economic 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 depends 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 et al., 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 1400 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 NCP 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 judgement 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 (Supplementary Material Tables S1-S6).

Given the complications involved in multiple sub-goals 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 low-medium-high 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 low to high 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. On the other hand, the NCP "regulation of climate" does not include an adaptation component, and refers to specifically to "positive or negative effects on emissions of greenhouse gases and positive or negative effects on biophysical feedbacks from vegetation cover to atmosphere" (Díaz et al., 2018). Thus, we evaluated only the relationship between response options and ecosystem impacts on local to global climate for this category.

Further, 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 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. Further, 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 multi-directional 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. Further, 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 makes 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). On the other hand, 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/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 Sustainable Development Goals

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 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 1400 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 non-commercial 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 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 NCP 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 out of the 40 have large potential (> 3 $GtCO_2e\ yr^{-1}$) 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

Decisionmakers 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 (forty 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.

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 (that is, those for which previous 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 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) is an important finding. This indicates there are potentially win-wins that do not require the degradation of natural capital and ecosystems to achieve poverty and development objectives (Miteva, 2019). 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 are 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, Van Noordwijk, 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 (Ilstedt et al., 2007), among other benefits. As a result, our assessment of this practice shows a range of positive benefits for both NCP and SDGs: for climate across 3 NCPs and 1 SDG (Climate Action); benefits for biodiversity across 4 NCPs and 1 SDG (Life on Land); and benefits for humans across 1 NCP (Supporting identities) and 5 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, seek to improve these in ways that have positive outcomes for both social and ecological components, while also minimizes 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; Seddon et al., 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 (Sachs et al, 2019; Iyer et al., 2018; 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 are conflicts 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 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 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). Further, because many of the NCPs and SDGs trade-off with one another (e.g. NCP 1 vs NCP 2, or NCP 2 vs SDG 4), 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 towards 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.

Further, all land-based options we assessed are scale dependent, and the potential adverse side-effects of practices such 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 multi-scalar, 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 (that is, 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. Further, given how important land management is for the supply of NCPs, we would expect more research to be conducted on the full range of NCPs from different land management practices, but certain NCPs have greater limitations in the literature than others (e.g. there is considerably less information on pollination services, air quality, or hazard regulation impacts linked to different specific land use practices).

4.5 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.

Further, 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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Table 1. Explanation of NCPs and SDGs

a. Sustainable Development Goals	**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
SDG4: Quality education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
SDG5: 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
SDG7: 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
SDG9: Industry, innovation and infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
SDG10: 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	Promote peaceful and inclusive societies for

institutions	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

b. Nature's Contributions to People	**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	Regulation, by ecosystems or organisms, of pests,

to humans	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
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

Table 2: Examples of search terms and literature found during review

Cell	Search terms	Examples of types of literature	Description of interaction in Supplementary	Basis for expert assessment

			Material	
Agroforestry & SDG 5 (Gender equity)	"agroforestry" + "gender" or "women*"	Meta-analysis for Africa (Kiptot, Franzel & Degrande, 2014). Field studies, East Africa (Gladwin et al., 2002)	Increased use of agroforestry can benefit female farmers as it requires low overhead (Gladwin et al., 2002), but land tenure issues must be paid attention to (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 US based on economic modelling (Goodwin & Smith 2003; Claasen et al., 2011) Regional (upper Midwest) data from land cover study (Wright & Wimberly, 2013)	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.	Literature all from US but generally in agreement that crop insurance has small negative impact on habitat due to association with crop expansion. *Final assessment*: Low negative impacts
Reduced deforestation and degradation & NCP 9 (Regulation	"Reduced deforestation" or "REDD" or "forest maintenance" + "hazard*" or	General literature review (Jactel et al., 2017; Locatelli et al., 2015)	Localized hazards like drought, floods and dust storms can be ameliorated by diverse tree cover,	Literature mostly about impact of hazards on diverse natural forests rather than direct effect of REDD on hazards per se; reducing

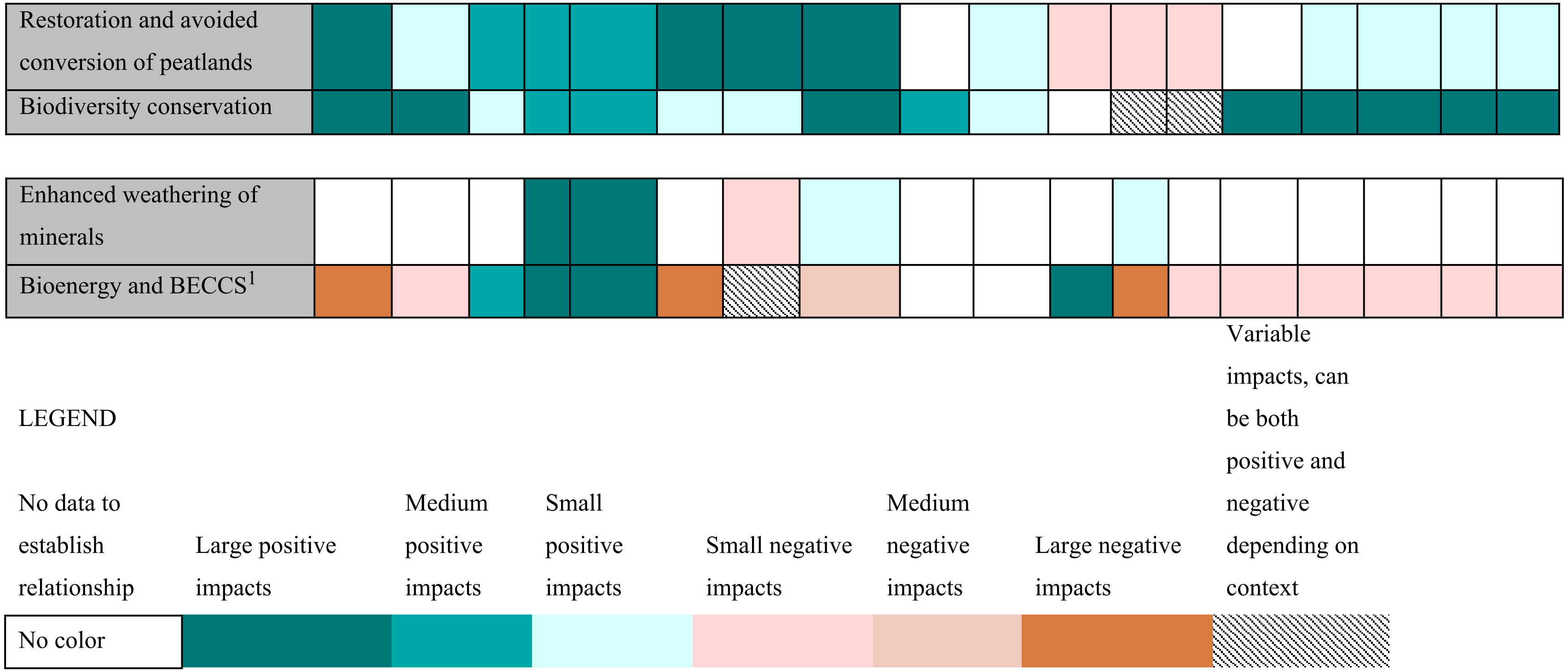
of hazards and extreme events)	"extreme event*"	Field experiments (Cooper-Ellis et al., 2009)	which would be encouraged by reduced deforestation (Cooper-Ellis et al., 2009; Jactel et al., 2017; Locatelli et al., 2015)	deforestation of forest areas leading to improvement in hazard regulation is implied 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 et al., 2013; Stathers, Lamboll & Myumi 2013) Systematic literature review (Hollis-Hansen et al., 2019) General literature reviews in multiple disciplines (Bradford et al., 2018; James & James, 2010; Keding, Schneider, & Jordan, 2013; Tirado et al., 2010; Vermeulen, Campbell, et al., 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 (Keding al., 2013; Vermeulen, Campbell, et al., 2012; Hollis-Hansen et al.	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

			2019)	

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																		
Fire management																		
Reduced landslides and natural hazards																		
Reduced pollution including acidification																		
Management of invasive species / encroachment																		
Restoration and avoided conversion of coastal wetlands																		



[1] Note that this refers to large areas of bioenergy crops capable of producing large mitigation benefits (> 3 $GtCO_2$ yr^{-1}). The effect of bioenergy and BECCS on NCPs is scale and context dependent, 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. 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
Dietary change																		
Reduced post-harvest losses																		
Reduced food waste (consumer or retailer)																		
Material substitution																		
Sustainable sourcing																		
Management of supply chains																		
Enhanced urban food systems																		
Improved food processing and retail																		

Improved energy use in food systems																		

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																		
Livelihood diversification																		
Use of local seeds																		
Disaster risk management																		
Risk sharing instruments																		

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

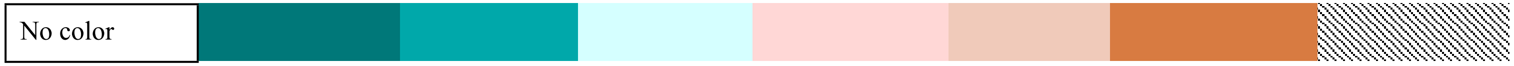
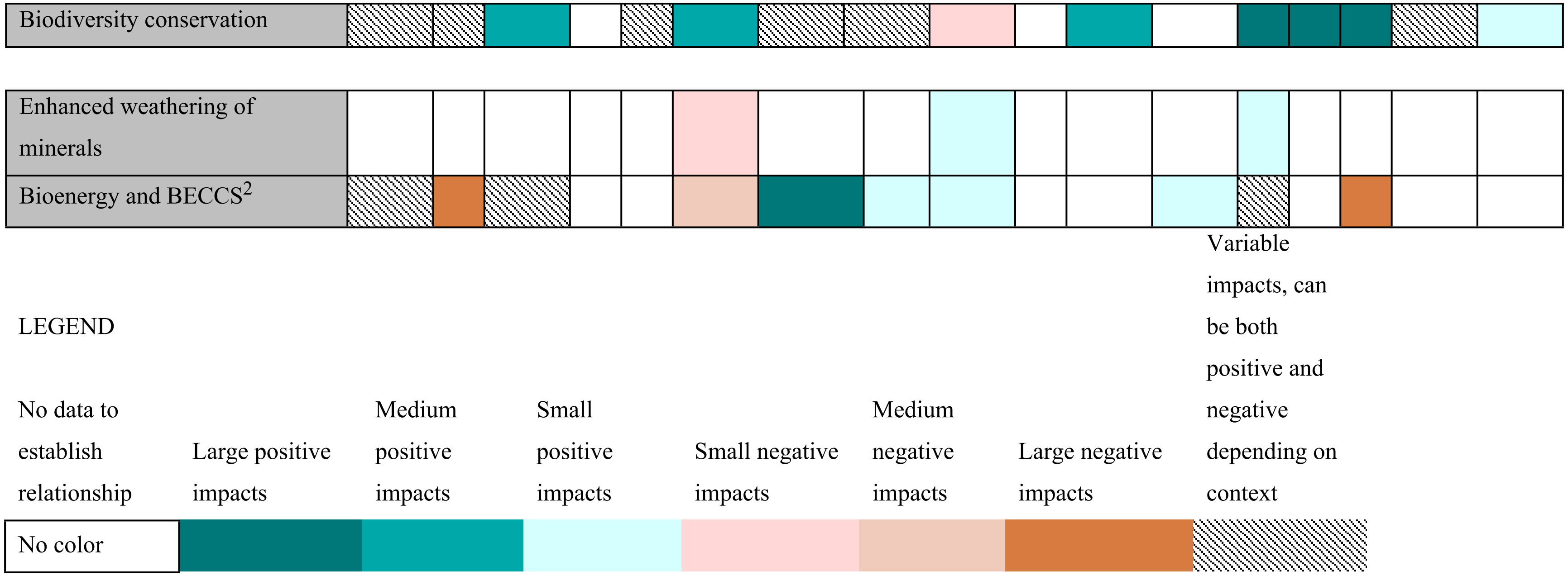


Table 6. Impacts on the UN SDG of integrated response options based on land management

Integrated response options based on land management	GOAL 1: No Poverty	GOAL 2: Zero Hunger	GOAL 3: Good Health and Well-being	GOAL 4: Quality Education	GOAL 5: Gender Equality	GOAL 6: Clean Water and Sanitation	GOAL 7: Affordable and Clean Energy	GOAL 8: Decent Work and Economic Growth	GOAL 9: Industry, Innovation and Infrastructure	GOAL 10: Reduced Inequality	GOAL 11: Sustainable Cities and Communities	GOAL 12: Responsible Consumption and Production	GOAL 13: Climate Action	GOAL 14: Life Below Water	GOAL 15: Life on Land	GOAL 16: Peace and Justice Strong Institutions	GOAL 17: Partnerships to achieve the Goal
Increased food productivity																	
Improved cropland management																	
Improved grazing land management																	
Improved livestock management																	
Agroforestry																	
Agricultural diversification																	
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																	
Fire management																	
Reduced landslides and natural hazards																	
Reduced pollution including acidification																	
Management of invasive species / encroachment																	
Restoration and avoided conversion of coastal wetlands																	
Restoration and avoided conversion of peatlands																	



[2] Note that this refers to large areas of bioenergy crops capable of producing large mitigation benefits (> 3 GtCO2 yr^{-1}). The effect of bioenergy and BECCS on 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	GOAL 1: No Poverty	GOAL 2: Zero Hunger	GOAL 3: Good Health and Well-being	GOAL 4: Quality Education	GOAL 5: Gender Equality	GOAL 6: Clean Water and Sanitation	GOAL 7: Affordable and Clean Energy	GOAL 8: Decent Work and Economic Growth	GOAL 9: Industry, Innovation and Infrastructure	GOAL 10: Reduced Inequality	GOAL 11: Sustainable Cities and Communities	GOAL 12: Responsible Consumption and Production	GOAL 13: Climate Action	GOAL 14: Life Below Water	GOAL 15: Life on Land	GOAL 16: Peace and Justice Strong Institutions	GOAL 17: Partnerships to achieve the Goal
Dietary change																	
Reduced post-harvest losses																	
Reduced food waste (consumer or retailer)																	
Material substitution																	
Sustainable sourcing																	
Management of supply chains																	
Enhanced urban food systems																	
Improved food processing & retail																	
Improved energy use in food systems																	

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	GOAL 1: No Poverty	GOAL 2: Zero Hunger	GOAL 3: Good Health and Well-being	GOAL 4: Quality Education	GOAL 5: Gender Equality	GOAL 6: Clean Water and Sanitation	GOAL 7: Affordable and Clean Energy	GOAL 8: Decent Work and Economic Growth	GOAL 9: Industry, Innovation and Infrastructure	GOAL 10: Reduced Inequality	GOAL 11: Sustainable Cities and Communities	GOAL 12: Responsible Consumption and Production	GOAL 13: Climate Action	GOAL 14: Life Below Water	GOAL 15: Life on Land	GOAL 16: Peace, Justice, Strong Institutions	GOAL 17: Partnerships to achieve the Goal
Management of urban sprawl																	
Livelihood diversification																	
Use of local seeds																	
Disaster risk management																	
Risk sharing instruments																	

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 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 et al., 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 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.	N/A
NCP 5 Regulation of ocean acidification	Bioenergy and BECCS will reduce ocean acidification by reducing CO_2 emissions and concentrations (IPCC, 2018; Doney, Fabry, Feely, & Kleypas, 2009);	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 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	Bioenergy can affect freshwater quality via changes in nitrogen runoff from fertilizer application. However, the sign	Likely to contribute to less pollution as local seeds are usually grown organically (Adhikari, 2014)

quality	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)	
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 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 (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	Local seeds can produce multifunctional materials (Adhikari, 2014).

NCP 14 Medicinal, biochemical and genetic resources	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 genetic resources	Many local seeds can have multiple functions, including producing medicinals (Hammer & Teklu, 2008)
NCP 15 Learning and inspiration	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 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 (Humpenöder et al., 2018; Smith et al., 2016; Clarke et al., 2014; Popp et al., 2017), it can reduce opportunities for recreation & tourism	N/A
NCP 17 Supporting identities	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 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 (Humpenöder et al., 2018; Smith et al., 2016; Clarke et al., 2014; Popp et al., 2017), it can reduce genetic diversity	Food sovereignty movements have promoted saving of genetic diversity of crops through on-farm maintenance (Isakson, 2009)

Table 10. Interactions between SDGs and two response options

SDG	Bioenergy and BECCS	Use of local seeds
GOAL 1: No Poverty	Bioenergy production could create jobs but could also compete for land with alternative uses (Humpenöder et al., 2018; Smith 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).	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)
GOAL 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; Popp, Lotze-Campen, et al., 2011; Smith, Haszeldine, & Smith, 2016; IPCC, 2018)	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 varieties.
GOAL 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 wellbeing 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)
GOAL 4: Quality Education	N/A	N/A
GOAL 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)

GOAL 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 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)	Local seeds often have lower water demands, as well as less use of pesticides that can contaminate water (Adhikari, 2014)
GOAL 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
GOAL 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
GOAL 9: Industry, Innovation and Infrastructure	BECCS will require development of new technologies (Smith, Haszeldine, & Smith, 2016)	N/A
GOAL 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.
GOAL 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)
GOAL 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).
GOAL 13: Climate Action	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).	Local seeds tend to be resilient to different climate hazards and thus can enhance adaptation (Louwaars 2002; Santilli 2012)
GOAL 14: Life Below Water	Bioenergy and BECCS will reduce ocean acidification by reducing CO_2 emissions and concentrations (IPCC, 2018; Doney, Fabry, Feely, & Kleypas, 2009)	N/A
GOAL 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)
GOAL 16: Peace and Justice 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).
GOAL 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)

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	Multi-directional NCP inter-actions	Multi-directional SDG inter-actions
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	8	7	1			

species / encroachment						
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		
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 3-8 and do not indicate magnitude of effect

Blue indicates presence of co-benefits with no noted adverse side-effects.

Brown indicates presence of multiple adverse side-effects across both SDGs and NCPs

Table 12. Highlighting response options for individual 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*), **agricultural 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*	**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*)
SDG5: Gender equity*	**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*)
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	**Disaster risk management**

Justice, strong institutions	*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

*Only moderate co-benefits were seen in these categories

Table 13. Highlighting response options for individual 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*)
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	*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,*

genetic resources	*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*)

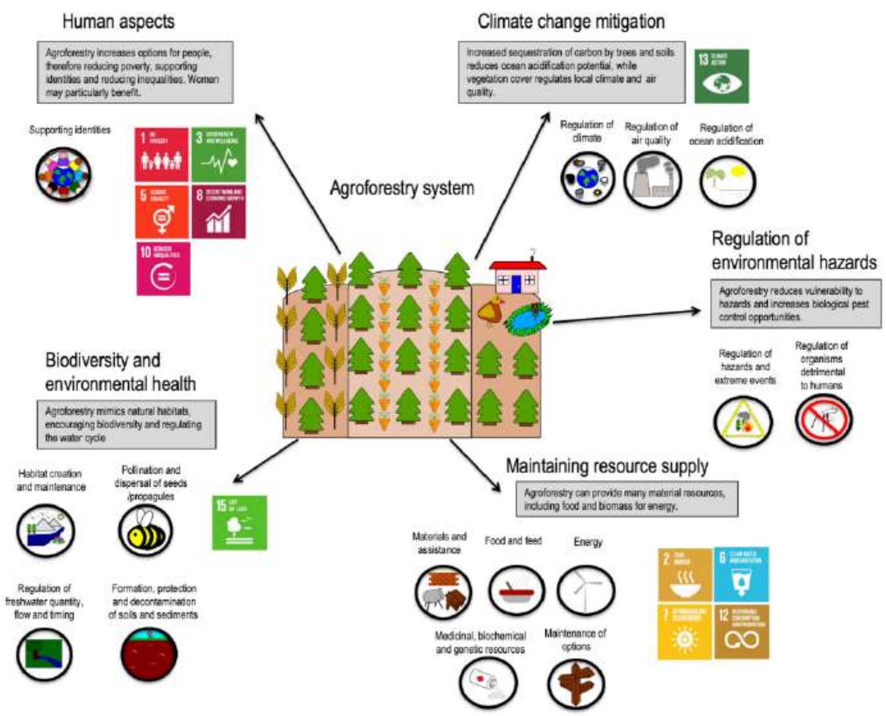


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Figure 1. Interactions between NCPs and SDGs within Agroforestry Systems. Note: Circles are key NCPs and squares are key SDGs.