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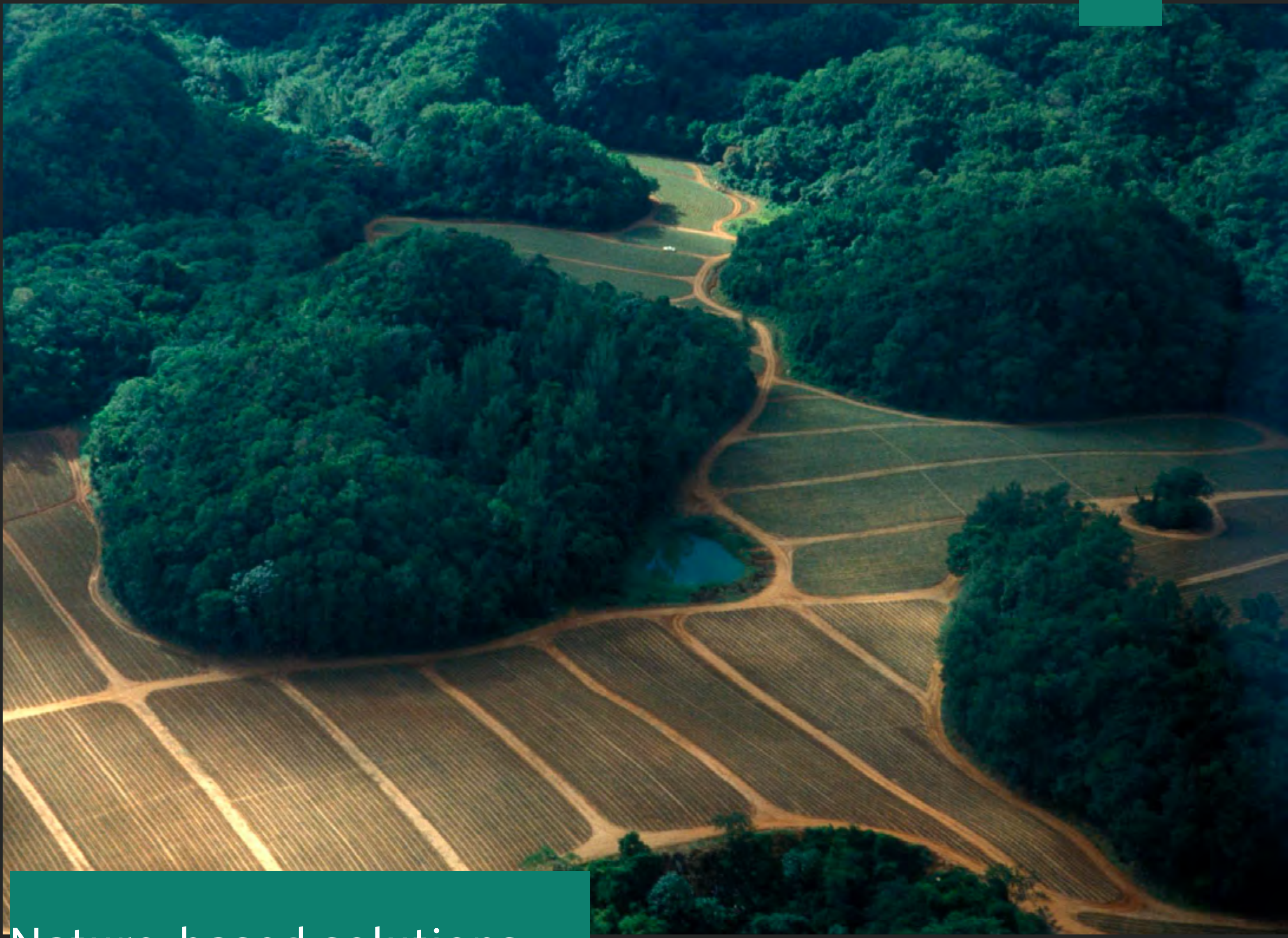

Nature-based solutions
in agriculture

Sustainable management and conservation of land, water, and biodiversity

The Nature Conservancy

NATURE-BASED SOLUTIONS IN AGRICULTURE

SUSTAINABLE MANAGEMENT AND CONSERVATION OF LAND, WATER AND BIODIVERSITY

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INTRODUCTION

NATURE-BASED SOLUTIONS IN AGRICULTURE: SUSTAINABLE MANAGEMENT AND CONSERVATION OF LAND, WATER, AND BIODIVERSITY

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BACKGROUND

In recent years, considerable progress has been made in the area of Nature-based Solutions (NbS) that improve ecosystem functions of environments and landscapes affected by agricultural practices and land degradation, while enhancing livelihoods and other social and cultural functions. This has opened up a portfolio of NbS options that offer a pragmatic way forward for simultaneously addressing conservation, climate and socioeconomic objectives while maintaining healthy and productive agricultural systems. NbS can mimic natural processes and build on land restoration and operational water-land management concepts that aim to simultaneously improve vegetation and water availability and quality, and raise agricultural productivity (Sonneveld *et al.*, 2018). NbS can involve conserving or rehabilitating natural ecosystems and/or the enhancement or the creation of natural processes in modified or artificial ecosystems (UNWWAP, 2018). In agricultural landscapes, NbS can be applied for soil health, soil moisture, carbon mitigation (through soil and forestry), downstream water quality protections, biodiversity benefits as well as agricultural production and supply chains to achieve net-zero environmental impacts while achieving food and water security, and meet climate goals.


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> NbS can involve **conserving or rehabilitating natural ecosystems and/or the enhancement or the creation of natural processes** in modified or artificial ecosystems .

METHODOLOGY

Many examples in the literature on agricultural practices have focused on highlighting production vs conservation tradeoffs, e.g., sparing versus sharing (Franklin and Mortensen, 2012), intensification vs sustainable production (Matocha *et al.*, 2012), agriculture vs forestry (Adewopo, 2019), or production forest vs. regeneration forest (Dewi *et al.*, 2013; Meyfroidt and Lambin, 2009), short-term economic gains versus long-term environmental benefits (Meyfroidt, 2018), among others. This literature review incorporates the application of NbS in agricultural landscapes that contribute to reducing negative trade-offs between sustainable production and conservation objectives. Specifically, this review provides a synthesis of literature covering NbS applications in agricultural landscapes to achieve co-benefits in production, climate action (disaster risk reduction, adaptation, and mitigation, and conservation of land, water and biodiversity.

To classify NbS in agricultural landscapes, we have drawn from several typology efforts employed in the literature. FAO has promoted a typology for NbS based on levels of human intervention (Eggermont *et al.*, 2015). TNC and collaborators have defined Natural Climate Solutions (TNC, 2020), as well as leverage the work of TNC's Water Funds (Abell *et al.*, 2017) which capture several NbS that intersect source water protection and agriculture, while providing co-benefits in climate, land and biodiversity. This has yielded a grouping of NbS as they apply in the forest, grassland and croplands, and wetland biomes. In doing this, the synthesis done in this document provides a broader context that is representative of major efforts in the international community centered on the application of NbS to a variety of global issues (e.g., IPCC for climate change, IPBES for biodiversity, among others).

The literature reviewed relies primarily in peer-reviewed sources, and is organized around a synthesis of NbS science and applications in agricultural landscapes in major biomes (forests, grasslands and croplands, and wetlands). These sources have been complemented with selected grey literature sources that provide evidence-based case study applications.


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For peer-reviewed literature, focus has been placed on the web of science, google scholar and science direct portals. Additionally, grey literature sources were obtained from organized literature outlets such as the World Overview of Conservation Approaches and Technologies (WOCAT), which focuses on documenting case study applications and best practices on NbS for sustainable land management (WOCAT, 2020). The Economics of Ecosystems and Biodiversity (TEEB) synthesis reports (TEEB, 2018a; TEEB, 2018b) were consulted to complement this review along the lines of economic considerations of ecosystem services in agriculture and food production. FAO's recent extensive report on The State of the World's Biodiversity for Food and Agriculture was drawn from as a key source of information linking biodiversity conservation to ecosystem services, provision of food security, resilience of food systems and support of livelihoods in agriculture.

This process yielded a significant body of literature sources with NbS applications across agricultural landscapes for a variety of objectives. In particular, literature sources on NbS related to climate mitigation (i.e., reduction of emissions and carbon sequestration) are far more numerous and delve deeper in analysis relative to NbS towards climate adaptation, conservation of land, water and biodiversity, and other ecosystem services and co-benefits. This is to be expected given the intense focus on the science of climate change globally and the maturity of efforts centered on mitigation sponsored by UNFCCC (e.g., IPCC, Green Climate Fund) and other global and regional organizations (e.g., World Bank Group, regional development banks). Because of

this asymmetry in available published work, this literature review has been structured by separately grouping the co-benefits provided by NbS into: (i) agricultural production; (ii) climate (mitigation and adaptation); (iii) conservation (biodiversity, land, water); and (iv) socioeconomic considerations of NbS in agricultural landscapes. Synergies across multiple co-benefits has been noted in some of the literature reviewed; this occurs particularly in the climate-related references, which often encompass conservation and other co-benefits.

To simplify the presentation of this literature review, the information has been organized into synthesis narratives accompanied by a series of tables that capture the characteristics of each NbS applied to each landscape to achieve agricultural production; climate (mitigation and adaptation), conservation (land, water, biodiversity) and other co-benefits. These tables have been adapted from the format followed in Griscom *et al.*, 2017, complemented with material from FAO, 2019 and other sources as cited.

> Synergies across multiple **co-benefits** has been noted in some of the literature reviewed

TABLE 1

Defines the various NbS synthesized in this review, a description containing some of the NbS key characteristics, and the assumptions embedded to specify each NbS in each one of the major biomes considered. Frameworks and guiding principles, are useful in guiding qualification and innovation in NbS. While the IUCN Global Standard for NbS has been a main reference for defining NbS, more recent frameworks include the development of an NbS planning tool specifically targeted at the agriculture sector (FAO and ICEM, [forthcoming] 2020).

TABLE 2

Provides examples of activities associated with NbS in agricultural landscapes that address agricultural production and other co-benefits.

TABLE 3

Summarizes the literature on conservation and climate adaptation co-benefits of the analyzed NbS for biodiversity, land, water and air.

TABLE 4

Provides key indicators and ranges of climate mitigation potential for each NbS over the next decade (time horizon of 2030).

TABLE 5

Complements the information in Table 2 by pairing NbS with mitigation costs to arrive at a parameterization of the tradeoff between investments in NbS and achieving climate benefits.

TABLE 1. SUMMARY OF NBS DEFINITION AND ASSUMPTIONS REGARDING EXTENT AND METHODS FOR ASSESSING AGRICULTURE, CONSERVATION, CLIMATE AND SOCIOECONOMIC CO-BENEFITS

NbS	Definition	Assumptions
AVOIDED FOREST CONVERSION	Forests are defined as areas with > 25 percent tree cover, per comprehensive global study conducted by University of Maryland team (Tyukavina *et al.*, 2012).	Boreal forests excluded due to albedo effect (offsets climate change) and because carbon stocks are significantly lower than those in tropical and subtropical areas. Most temperate forests excluded due to lack of data and to avoid double-counting tree cover loss associated with temperate forestry. Wetland forests (mangroves, peatlands) excluded to avoid double-counting with wetland NbS. Excludes loss of "managed forest" as defined by Tyukavina *et al.*, except for inclusion of emission attributed to conversion to subsistence agriculture. Given these exclusions, this NbS has no spatial overlap with others.
REFORESTATION	Conversion from non-forest (< 25% tree cover) to forest (> 25% tree cover in areas ecologically appropriate and desirable for forests.	We exclude afforestation, defined here as conversion of native non-forest cover types (i.e. grassland, savanna, and transitional areas with forest) to forest. Boreal biome excluded, due to albedo. All existing cropland area excluded, due to food security safeguard. Exclusion of croplands from reforestation while assuming that all grazing lands in forested ecoregions can be reforested is consistent with recent analyses finding a variety of options for improving the efficiency of livestock production and/or diet change (Erb *et al.*, 2016; Herrero *et al.* 2013). Impervious surfaces excluded.
NATURAL FOREST MANAGEMENT	Improved forest management practices in native forests under timber production. This definition applies to naturally-regenerated forests designated for production or multiple-use as defined by FAO (FAO, 2020).	Includes all native forests under timber production in tropical, subtropical, temperate, and boreal climate domains. Does not involve transitions between "forest" and "non-forest" or management for tree species changes, so does not invoke albedo changes. Excludes areas under intensive plantation forestry. Includes areas also included in Fire Management, but double counting avoided because it is assumed that no improvements are made in fire management.

NbS	Definition	Assumptions
MAINTAINING RIVERINE ECOSYSTEMS AS NATURAL FLOOD DEFENCES	Natural flood defences, including wetlands, lakes and rivers, are meant to absorb flood waters and provide the space needed to reduce flood risk (Day *et al.*, 2007; van Wesenbeeck *et al.*, 2017). The restoration of inactive floodplains can also contribute to reducing carbon emissions and "building back better" by enhancing retention and nutrient cycling to improve water quality (Ramsar Convention on Wetlands, 2018)	Wetlands play a key role in the global water cycle, particularly through water purification, and nutrient cycling. Wetland flood mitigation potential is dependant on geographic location, the interaction of the wetland area with other flood defences and the potential flood waters, and what alternative flood uses could have been (TEEB, 2013). Peatlands, wet grasslands and other wetlands can reduce the speed and volume of runoff after heavy rainfall, by storing and slowly releasing water or snowmelt (Javaheri and Babbar-Sebens, 2014; Acreman and Holden, 2013).
IMPROVED PLANTATIONS	Extending harvest rotation lengths on intensively managed production forests (i.e. plantations) subject to even-aged stand management.	Includes intensively managed production forests (i.e. plantations) subject to even-aged stand management in tropical, subtropical, temperate, and boreal climate domains. Does not involve transitions between "forest" and "non-forest" or management for tree species changes, so does not invoke albedo changes. Excludes areas not under intensive plantation forestry.
FIRE MANAGEMENT	Integrates three spatially discrete and distinct forms of fire management (i) prescribed fires applied to fire-prone temperate forests to reduce the likelihood of more intense wildfires; (ii) fire control practices (e.g. fire breaks) applied in moist and wet tropical forests to avoid understory fires that enter at edges with lands converted to non-forest cover types (primarily pasture maintained with fire); and (iii) use of early season fires in savanna ecosystems to avoid higher emissions late season fires.	Includes naturally fire-prone forests in North America and Europe, forests adjacent to pasture in Brazilian Amazonia, and global savannas. Extent is conservative because full potential extent of application of this NbS is larger but unknown. This has spatial overlap with Natural Forest Management; however, no double-counting issues because this NbS assumes no change in harvest levels.
AVOIDED WOODFUEL HARVEST	Drawn from a recent comprehensive analysis of global unsustainable woodfuel harvest levels (Bailis *et al.*, 2015).	Extent is not spatial, but based on number of people, the majority in Africa. Potential spatial overlap with savanna burning; however, no double-counting since this NbS and improved savanna fire management are additive. No double counting with Avoided Forest Conversion by subtracting the 32% of baseline woodfuel harvest emissions linked to forest conversion (Bailis *et al.*, 2015).

NbS	Definition	Assumptions
AVOIDED GRASSLAND CONVERSION	Includes temperate grasslands, tropical savannas, and shrublands; focus is placed on conversion of grasslands to cropland.	Includes avoided conversion to cropland of tropical, subtropical, and temperate native grasslands. Spatial overlap with other NbS (e.g. fire management) is minimum.
BIOCHAR	Amount of crop residue available for pyrolysis, used as a soil amendment for both carbon sequestration and soil health benefits.	Crop residue availability for biochar estimated from assumptions about global crop production, competing demands for residue, and the fraction of residue that must be left in fields to maintain soil condition and carbon levels (Slade, Bauen and Gross, 2014; Slade and UKERC (Organization), 2011). Maximum extent assumed to be all global croplands. This has spatial overlap with Cropland Nutrient Management, Conservation Agriculture, and Trees in Croplands. However, accounting of carbon mitigation benefits is additive so no double-counting deductions needed.
CROPLAND NUTRIENT MANAGEMENT	Business as usual nutrient budgets from Bodirsky *et al.*, who use a range of development scenarios to project total food and feed demand to 2050. (Bodirsky *et al.*, 2014)	Bodirsky *et al.* develop country-specific nitrogen budgets balancing nutrient demand (crop and livestock production) and supply (atmospheric deposition, manure, legumes etc.). Based on a series of assumptions about nitrogen use efficiency, they then estimate the amount of synthetic and manure fertilizer needed to meet nutrient shortfalls in different regions. The end result is a projected amount of nitrogen fertilizer applied in order to meet global food demand to 2050. Applicable extent includes all global croplands, except those already using best nutrient management practices. Spatial overlap with Biochar, Conservation Agriculture, and Trees in Croplands; however, no double-counting for mitigation purposes because this considers different pools and fluxes (N2O flux, measured in Mg of fertilizer, rather than soil carbon and biomass carbon pools) and likewise accounting is additive to these other NbS.

NbS	Definition	Assumptions
CONSERVATION AGRICULTURE	Cultivation of cover crops in fallow periods between main crops. Prevents losses of arable land while regenerating degraded lands. Promotes maintenance of a permanent soil cover, minimum soil disturbance, and diversification of plant species. Enhances biodiversity and natural biological processes above and below the ground surface, which contribute to increased water and nutrient use efficiency and to improved and sustained crop production.	Limited to active global cropland areas where cover crops are not currently used but could be given climatic and crop system context. Spatial overlap with Biochar, Nutrient Management, and Trees in Croplands. Carbon mitigation accounting is additive so no double-counting concerns.
TREES IN CROPLANDS	Includes windbreaks (shelterbelts), alley cropping, and farmer managed natural regeneration (FMNR), each of which was restricted to non-overlapping relevant cropland areas.	Applicable area for windbreaks and/or alley cropping includes annual croplands currently with <10% tree cover, excluding African cropland (where FMNR was exclusively applied). Any production system that exceeds 25% tree cover (e.g. some agroforestry) and all silvopastoral systems (outside of croplands) were excluded to avoid double counting with Reforestation. Spatial overlap with Biochar, Nutrient Management, Conservation Agriculture; however, accounting is additive, so no carbon double-counting concerns.
GRAZING - OPTIMAL INTENSITY	Grazing optimization defined as the offtake rate that leads to maximum forage production (Henderson *et al.*, 2015). This prescribes a decrease in stocking rates in areas that are overgrazed and an increase in stocking rates in areas that are undergrazed, but with the net result of increased forage offtake and livestock production.	Includes global rangelands and planted pastures. Spatial overlap with Reforestation and Grazing - Legumes. Mitigation potential of this NbS was subtracted from Reforestation mitigation potential to avoid double-counting. Accounting with Grazing - Legumes is additive, so no mitigation double-counting concerns.
GRAZING - LEGUMES IN PASTURES	Sowing legumes in planted pastures.	Restricted to global planted pastures. Spatial overlap with Reforestation and Grazing - Optimal Intensity. Mitigation potential of this was subtracted from Reforestation mitigation potential to avoid double-counting. Accounting with Grazing - Optimal Intensity is additive, so no double-counting concerns.

NbS	Definition	Assumptions
GRAZING - IMPROVED FEED	Improved feed management represents inclusion of energy-dense feeds (e.g. cereal grains) in the ration, with the greatest potential in production systems that utilize little or no grain to feed animals, which are common in many parts of the world. (Herrero *et al.*, 2016)	Spatial overlap with other grazing NbS, but accounting additive so no double-counting concerns. This has the added benefit of sparing land as a result of the reductions in the extent of land needed for livestock production (Havlík *et al.*, 2014); however, this benefit is not accounted for here to avoid double-counting with avoided deforestation and reforestation.
GRAZING - ANIMAL MANAGEMENT	Use of improved livestock breeds, and increased reproductive performance, health, and liveweight gain.	Spatial overlap with other grazing NbS, but accounting additive so no double-counting concerns. This has the added benefit of sparing land as a result of the reductions in the extent of land needed for livestock production (Havlík *et al.*, 2014); however, this benefit is not accounted for here to avoid double-counting with avoided deforestation and reforestation.
IMPROVED RICE CULTIVATION	Water management techniques such as alternate wetting and drying and midseason drainage limit the time rice paddies spend in an anaerobic state thereby reduce annual methane emissions while at the same time saving water (Sander, Wassmann and Siopongco, 2015). Additional management techniques applied to upland rice such as fertilizer applications, residue and tillage management practices reduce the amounts of nitrogen and carbon emissions.	Global upland and flooded rice lands included. Limited spatial overlap with Biochar, Trees in Croplands, and Nutrient Management; however, accounting is additive, so no carbon mitigation double-counting concerns.
AVOIDED COASTAL WETLAND IMPACTS	Coastal wetland conversion causes anthropogenic loss of organic carbon stocks in mangroves, saltmarshes, and seagrass ecosystems. (U.S. EPA, 2016)	Includes global mangroves, salt marshes, and coastal seagrass. Mangroves were excluded from Avoided Forest Conversion to avoid double-counting.
PEATLAND RESTORATION	Potential extent of peatland restoration based on the extent of degraded wetlands, derived from (Joosten, 2009).	Includes restoration of global non-tidal freshwater forested and non-forested wetlands.

NbS	Definition	Assumptions
AVOIDED PEATLAND IMPACTS	Conversion rate of freshwater peatlands per The International Mire Conservation Group Global Peatland Database (Joosten, 2009).	Includes all non-tidal freshwater forested and non-forested wetlands. Forested wetlands were excluded from Avoided Forest Conversion to avoid mitigation double-counting.
COASTAL WETLAND RESTORATION	Potential extent of wetland restoration based on the extent of degraded wetlands, derived from estimate of percent of original extent disturbed, restoration of mangroves and seagrass (Mcleod *et al.*, 2011).	Includes restoration of global mangroves, salt marshes, and coastal seagrass.
PEATLAND RESTORATION	Potential extent of peatland restoration based on the extent of degraded wetlands, derived from (Joosten, 2009).	Includes restoration of global non-tidal freshwater forested and non-forested wetlands.

NBS AND FOOD PRODUCTION-DERIVED CO-BENEFITS

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Examples of experiencies in implementation of NbS in agricultural landscapes do suggest however a variety of **co-benefits specific to production**.

Case studies and quantification of benefits of NbS in agricultural landscapes have had a dominant focus on carbon sequestration, water, disaster-risk management and urban environments (Cohen-Shacham *et al.*, 2016; FOLU, 2019), while specific examples of NbS benefits in agricultural production are sparse. For instance, in the Special Report on Climate Change and Land, while forestry and water management are featured among the five NbS response options on 'land management', none explicitly stated agriculture (Hurlbert *et al.*, 2019) and in the same report, urban agriculture is reported under management of supply rather than of land, focusing NbS away from agricultural landscapes.

Examples of experiences in implementation of NbS in agricultural landscapes do suggest however a variety of co-benefits specific to production. For instance, some production-oriented practices make use of the multiple ecosystem functions of trees, plants and (wild or domesticated) animals for agricultural production, while minimizing the negative environmental impacts of the production (Darayanto *et al.*, 2018) as regenerative agriculture and conservation agriculture. Other documented practices are aimed at retaining or increasing available nutrients or improving the microclimate. For example, trees in alley cropping can provide shade among other roles, e.g., tree crops for food and fodder production, perennial alley crops, trees for crop facilitation via shade, within-system tree diversity (Wolz and DeLucia, 2018).

Many sustainable practices and approaches drawing on agroecological principles (Altieri, 1992; FAO, 2018) or collectively referred to as climate-smart agriculture (FAO, 2013; Rosenstock *et al.*, 2019), would also fall into this category. Specifically, in agroforestry and sloping agriculture land technologies, in addition to production contributions, plants may also perform NbS functions if, for example, planted as grass strips, or nitrogen-fixing legumes used as green mulch and fruit trees, planted along contours (Are, Oshunsanya and Oluwatosin, 2018; Aguiar Jr. *et al.*, 2015; McIvor *et al.*, 2014).

When agricultural species play the role of vegetation in NbS, multiple functions are rendered. For example, grass strips control soil erosion and return crop yields (Rosenstock, Rohrbach, Nowak, 2019) and vetiver grass can act as phytoremediation to trap phosphorous (Huang *et al.*, 2019) while providing cut for animal feed. The efficiency of a catch crop also depends on physical elements, such as slope gradient (Novara *et al.*, 2019) and root structure. Some papers related microterraces and built terraces as NbS for agriculture (Zuazo *et al.*, 2011; Liu *et al.*, 2018). In northern India for example, simple weed strips and weed mulch also created microterraces, which resulted in reduced soil erosion and higher yields (Lenka *et al.*, 2017).

Other experiences are illustrative of agriculture-derived co-benefits of NbS. For instance, trees in croplands or agroforestry (Francis *et al.*, 2003) is an increasingly prominent example of a working landscape practice that can provide multiple economic, cultural and ecological benefits (FAO, 2005; World Agroforestry Centre, 2008). Agroforestry's diversified cropping systems mimicking natural forests form an important part of indigenous food production systems around the world and are also being used as a contemporary agricultural BMP in non-traditional contexts. These systems tend to be resilient, productive, pest resistant, nutrient-conserving and biodiverse, providing multiple economic, cultural and ecological benefits (Ewel, 1999). For example, they can provide fuelwood, cultivated foods, timber and medicinal plants for local communities (Junsongduang *et al.*, 2013; Thaman, 2014), while also supporting high levels of biodiversity (Thaman, 2014; ASFAW and LEMENIH, 2010; Jose, 2009). These systems have also been shown to reduce sediment and nutrient runoff into adjacent watercourses and enhance carbon sequestration and storage (Bruun *et al.*, 2009; Montagnini and Nair, 2004). Agroforestry


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Documented practices are aimed at **retaining or increasing available nutrients or improving the microclimate.**


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systems also support a diversity of wild foods and provide pollinator habitat, both of which can help to combat malnutrition and micronutrient deficiencies (Declerck *et al.*, 2011; Chaplin-Kramer *et al.*, 2014; Johns, 2003; Steyn *et al.*, 2006; Ellis, Myers and Ricketts, 2015). A subset of agroforestry, silvopasture, integrates trees with pasture with the intention of increasing pasture quality and producing fodder while also protecting soils and vegetation.

Another type of agricultural NbS, conservation agriculture, defined by a combination of conservation tillage, crop rotations, and cover crops has gained traction in many parts of the world. In some regions, variations on the principles of conservation agriculture have been part of traditional agricultural systems for generations. As of 2011, conservation agriculture had been implemented on approximately 125 million hectares across the world, with the greatest concentrations by far in United States, Brazil, Argentina, Australia, and Canada (Friedrich, Derpsch and Kassam, 2012). The broad extent of this adoption has been cited as evidence of its implicit benefits for farmers (Brouder and Gomez-Macpherson, 2014).

There is clear evidence that conservation agriculture increases soil organic matter and a range of associated processes including improved sediment retention. However, crop yield outcomes vary based on practices employed, climate, crop type, and biophysical conditions (Palm *et al.*, 2014). Available evidence on actual changes in crop yields suggests that conservation agriculture has the greatest potential to increase crop yields when implemented as a set of integrated practices in rainfed systems in water-limited or water-stressed regions, including potentially on millions of hectares in Sub-Saharan Africa and South Asia. Decisions to adopt conservation agriculture practices can go beyond immediate changes in crop yield, though. For example, a review of farmer adoption of conservation agriculture, identified reduction in farm operation costs, nutrient use and efficiency, water savings, and crop yield stability as additional factors beyond increased crop yield that motivated adoption (Corsi and Muminjanov, 2019).

Intensification of agriculture has been reported in the literature, both from a perspective of increased production and conservation perspective; the latter in terms of the millions of hectares of forests which otherwise would be converted into farm land, provision of ecosystem services, and of some 590 billion tons of carbon prevented from being released into the atmosphere (Burney, Davis and Lobell, 2010). Rockström *et al.* (2017) describe the conditions and the elements of mainstreaming sustainable agricultural intensification in order to reposition agriculture from being the major driver of global environmental change to a major contributor to the transition to sustainability through incorporating double objectives of increasing yields and enhancing the ecosystem services.

> There is clear evidence that **conservation agriculture** increases soil organic matter and a range of associated processes including improved sediment retention.

Similarly, though outside of what is typically considered agricultural lands, NbS can also lead to co-benefits in relation to food production in seascapes. The


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Special Report on the Ocean and Cryosphere in a Changing Climate has singled out fisheries and aquaculture as one of the human activities exposed and vulnerable to climate drivers and discussed NbS as potential effective pathways to risk reduction for marine dependent communities including fishing and fish farming communities (IPCC, 2019). Coastal and riverine ecosystems are critical for production of wild fish, for some of the 'seed' and much of the feed for aquaculture. The conservation and restoration of aquatic ecosystems are considered to be essential pieces of the portfolio of NbS measures to mitigate and adapt to global climate change: fish and fish products are rich in nutrients and micronutrients and have low carbon footprint; moreover, healthy aquatic and coastal ecosystems, such as estuaries, coral reefs, mangroves and seagrass beds not only sustain the productivity of fisheries and aquaculture and sequester and store carbon, they are also more resilient and hence more likely to absorb changes resulting from global warming, or moderate the impacts when these changes are abrupt, as in the case of extreme events or disasters.

Table 2 lists some illustrative agriculture-derived co-benefits of NbS, and activities that have been documented to realize these benefits. While a detailed characterization of these co-benefits, particularly in socioeconomic terms, remains to be done, it is anticipated that upscaling implementation will need to adapt practices and strategies to the local biophysical, economic, and socio-cultural context and work to integrate local knowledge for effective results. Where they do so, existing sustainable agricultural systems can be supported and less sustainable practices shifted towards mutually beneficial outcomes for agricultural producers and broader society.

TABLE 2. ILLUSTRATIVE CO-BENEFITS AND ACTIVITIES ASSOCIATED WITH NBS IN AGRICULTURAL

Activities represent a variety of NbS applications that address agricultural production while providing co-benefits (e.g., environmental, sustainability); adapted from (Griscom *et al.*, 2017; FAO, 2019).

NbS	Example Co-Benefits and Activities
FORESTS	
AVOIDED FOREST CONVERSION	Protected areas establishment; improved siting of non-forest land use; improved land tenure; zero-deforestation commitments; sustainable intensification of subsistence agriculture; avoided loss of high carbon forests. (Altieri, 2002; Ayarza *et al.*, 2010; Abell *et al.*, 2019; Kroeger *et al.*, 2019)
REFORESTATION	Conversion from non-forest to forest in areas ecologically appropriate for tree growth through agricultural certification programs and impact mitigation frameworks that prioritize restoration; regulations that advance minimum forest cover requirements; integration of trees into grazing lands (i.e. silvopastoral systems); reduced consumption of land-extensive food types (e.g. beef). (Kosoy *et al.*, 2007; Cole, 2010; Locatelli, Rojas and Salinas, 2008; Lerner *et al.*, 2017; Chará *et al.*, 2019; Niijima and Yamane, 1991; Trabucco *et al.*, 2008)
NATURAL FOREST MANAGEMENT	Extension of logging rotations; reduced-impact logging practices that avoid damage to non-commercial trees; improved land tenure (IPCC, 2006).
FIRE MANAGEMENT	Advance prescribed fires to reduce the likelihood of more intense wildfires in fire-adapted forests; advance fire control practices in tropical moist forests such as fire breaks between pasture and forest edges; improved forest management practices that reduce slash and improve resiliency to natural disturbance. (Wiedinmyer and Hurteau, 2010; Alencar, Nepstad and Diaz, 2006; Anderson *et al.*, 2015)
IMPROVED PLANTATIONS	Extension of logging rotation lengths to achieve maximum yield while increasing average landscape carbon stocks; multi-species plantation systems. (Nowak *et al.*, 2013; Nowak *et al.*, 2014; Harrison, Wardell-Johnson and McAlpine, 2003; van der Werf *et al.*, 2010)
AVOIDED WOODFUEL HARVEST	Reduce woodfuel harvest levels by the adoption of improved efficiency cookstoves or stoves using alternative fuel (e.g. solar, methane from agricultural waste).

NbS	Example Co-Benefits and Activities
AGRICULTURE & GRASSLANDS	
AVOIDED GRASSLAND CONVERSION	Protected areas establishment and improved enforcement to prevent the conversion of grasslands to tilled croplands; improved land tenure; intensification of existing croplands (Burivalova, Şekercioğlu and Koh, 2014; Burton, 1997; Bremer, 2014; Bremer *et al.*, 2014; Don, Schumacher and Freibauer, 2011)
BIOCHAR	Extension programs to build capacity on biochar management; improved land tenure; certification systems; incentives programs (Saeid and Chojnacka, 2019; Davidson and Ackerman, 1993; Bell and Worrall, 2011)
CROPLAND NUTRIENT MANAGEMENT	Certification programs that seek to maintain water quality by reducing excessive fertilizer; water quality/pollution mitigation; credit trading programs; removal of regulations creating perverse incentives to apply excessive fertilizer; improved manure management (Keeler *et al.*, 2012; Oenema *et al.*, 2014; Mueller *et al.*, 2014; Snyder *et al.*, 2009)
CONSERVATION AGRICULTURE	Cultivation of additional cover crops in fallow periods; shift to reduced-tillage or zero-tillage systems and other conservation agriculture practices may enhance soil carbon benefits of cover crops (Keeler *et al.*, 2012; FAO, 2008; Benites and Ofori, 1993; ESMC, 2018; Pueppke *et al.*, 2019;World Bank, 2018; Lewis *et al.*, 2019; Faiz-ul Islam *et al.*, 2020)
TREES IN CROPLANDS	Regulations and certification programs that promote the integration of trees into agricultural lands; agroforestry certification systems; increasing the number of trees in croplands by introducing windbreaks (also called shelterbelts), alley cropping, and farmer-managed natural regeneration (FMNR) (Poeplau and Don, 2015; Zomer *et al.*, 2008; Kumar and Nair, 2011; Chendev *et al.*, 2014)
GRAZING - ANIMAL MANAGEMENT	Animal management practices such as improved health; reduced mortality; improved genetics; live weight gain (Davidson, 2009)
GRAZING - OPTIMAL INTENSITY	Maintaining forage consumption rates that enable maximum forage production; certification programs (Page *et al.*, 2002).
GRAZING - LEGUMES IN PASTURES	Sowing legumes in existing planted pastures.
GRAZING - IMPROVED FEED	Inclusion of cereal grains in feed to improve feed quality and reduce methane emissions.
IMPROVED RICE CULTIVATION	Adopting water management techniques such as alternate wetting and drying (AWD) and midseason drainage (MSD); residue incorporation; fertilizer management (Wang *et al.*, 2013)

NbS	Example Co-Benefits and Activities
WETLANDS	
AVOIDED COASTAL WETLAND IMPACTS	Protected areas establishment and improved enforcement; improved land tenure; no-net-loss mitigation regulations; avoided harvest of mangroves for charcoal; avoided consumption of food products with acute impacts on coastal wetlands (e.g. mangrove replacing shrimp farms) (Heumann, 2011; Polidoro *et al.*, 2010; Zedler, 2003; Breaux, Farber and Day, 1995)
AVOIDED PEATLAND IMPACTS	Protected areas establishment and improved enforcement; improved land tenure; no-net-loss mitigation regulations; resiting of oil palm plantation permits to non-peat locations (Spitzer and Danks, 2005; Page *et al.*, 2002; Schoeneberger, 2008)
WETLANDS RESTORATION	Re-wetting and re-planting with native salt-water wetlands; wetland mitigation programs. (Ming *et al.*, 2007; Giri *et al.*, 2011; Siikamäki, Sanchirico and Jardine, 2012; Jardine and Siikamäki, 2014; Donato *et al.*, 2011)
PEATLAND RESTORATION	Re-wetting and re-planting with native freshwater wetlands species; wetland mitigation programs (Pendleton *et al.*, 2012)

Besides agriculture, there are noteworthy examples of NbS in aquaculture and fisheries. For instance, Restorative Aquaculture is the expansion of unfed, low trophic marine aquaculture, primarily of bivalve shellfish and seaweed, which require very low utilization of resources from a life cycle analysis perspective, and also provide ecosystem services back to the environment, in the form of provisioning services, regulating services and habitat services. FAO developed the Ecosystem Approach to Aquaculture (FAO, 2001) which is commonly cited in the aquaculture literature as a framework or road map for responsible development of the aquaculture sector.

Another example in the aquaculture space is Integrated Multi-Trophic Aquaculture (Soto and FAO, 2009) which involves culturing fish alongside shellfish and seaweed providing potential win-wins for sustainable food production and opportunities to restore coastal ecosystems. The idea is that the shellfish and seaweed aquaculture will utilize nutrients from the fish farm, thereby reducing effects of effluent. Wide scale implementation of this NbS has been limited though as experience on the ground increasingly shows that most of the negative impacts of fish farms on water quality can be mitigated just through good site selection (Theuerkauf *et al.*, 2019).

On the fisheries side, implementation of sustainable fisheries management measures provides the strongest and most powerful mechanism to allow fish populations, marine ecosystems, and fishing- and coastal-based economies to thrive. Rebuilding of fish populations has been demonstrated in global fisheries that are managed (Hillborn *et al.*, 2020). Yet, many data- and resource-limited fisheries face challenges in access the tools and capacity needed to effectively allow fish populations to recover (Dowling *et al.*, 2016). Recent literature illusrtaes how we can ensure nature-related biodiversity goals are met, while simultaneously meeting the demand for food from the sea, by implementing effective fisheries management measures (Costello *et al.*, 2020; Hillborn *et al.*, 2020).

Implementing an ecosystem-based fisheries management (EBFM) or an ecosystem approach to fisheries (EAF) ensures management measures are taken with a holistic, ecosystem perspective (FAO EAF Toolbox[1]). Maintaining healthy ecosystem function and reducing overfishing is also critical for climate change resilience in marine fisheries (Sumalia and Tai, 2020).

Coastal habitat conservation and restoration allows nature to thrive and ensures healthy marine ecosystems, necessary to produce stable, sustainable supplies of seafood. Spatial management measures, or specific restrictions such as fishing gear regulations can serve to protect critical habitat, such as seagrass beds that may serve as nursery grounds for important fished species, or spawning zones (Guannel *et al.*, 2016; MacNeil *et al.*, 2015).

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[1] FAO EAF Toolbox: http://www.fao.org/fishery/eaf-net/toolbox/en

CONSERVATION AND ADAPTATION CO-BENEFITS OF NBS

NATURE-BASED SOLUTIONS IN AGRICULTURE: SUSTAINABLE MANAGEMENT AND CONSERVATION OF LAND, WATER, AND BIODIVERSITY


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The recognition of NbS towards conservation and adaptation co-benefits has been increasingly documented in the literature in recent years. This section documents literature sources in conservation and adaptation associated with each of the NbS defined in Table 1. For consistency, a taxonomy of conservation actions developed by the International Union for Conservation of Nature (IUCN) and the Conservation Measure Partnership (Holt *et al.*, 2016) was used to link each NbS with a known set of conservation activities. Activities represent specific conservation, restoration, and improved land management actions that practitioners may take that are nature-based. For adaptation, focus is placed on co-benefits related to water resources (e.g., flood and drought management), extreme weather events, developing drought-tolerant crops, choosing tree species and forestry practices less vulnerable to storms and fires, and other similar activities.

Various agricultural landscape approaches have been documented to achieve multiple goals from ecological intensification of crop production with biodiversity focus to ecosystem services within payment-for-ecosystem-services (PES) schemes (Holt *et al.*, 2016; Karabulut, Udias and Vigiak, 2019; van Noordwijk *et al.*, 2019). One particular intention with practices in this category, is to ensure ecological connectivity of conservation agriculture on field-units across larger landscape mosaics in landscape approaches (Karabulut, Udias and Vigiak, 2019). Furthermore, species diversity play important roles for recovery after disaster and preventive disaster risk reduction, such as mangroves protecting against storm surges (van Noordwijk *et al.*, 2019).

Other cases in the literature illustrate the integration of practices to connect patches in the landscape. A number of cases across Europe implemented agrobiodiversity approaches, where permanent grassland and crop diversification within ecological focus areas involved a certain percent of arable land set aside to be used for field margins, hedges, trees, fallow land, landscape features, biotopes, buffer strips, and afforested areas (Delbaere, Mikos and Pulleman, 2014). Similarly, connectivity was achieved with ecological infrastructure such as woodland hedges, grass strips, wildflower strips, and field margins (Rosas-Ramos *et al.*, 2018). In Pakistan, an example of NbS practices include crop rotation, intercropping, agroforestry, crop diversification, live fencing, and wind barriers by trees (Shah, Zhou and Shah, 2019). These example illustrates a combination of practices that build up multiple conservation objectives and also contribute to climate mitigation.

For classification purposes, conservation co-benefits considered in this review fall into four generalized types of ecosystem services (biodiversity, water, soil, air) that may be enhanced as a result of the implementation of NbS (Table 3). Types of ecosystem services are linked

Conservation co-benefits considered in this review fall into four generalized types of ecosystem services;

biodiversity

water

soil

air

to an NbS only where one or more peer-reviewed publication confirms that the type of ecosystem service is enhanced by implementation of that NbS. For example, the existence of additional forest area (which is generated by avoided forest conversion and reforestation pathways) has been linked to improved air quality (Kroeger *et al.*, 2014). However, two forest management NbS in this review (natural forest management, improved plantations) do not directly change forest area, so a link between forestry management pathways and improved air quality has not been included here. Such a link may exist, but documentation of it in a peer-reviewed publication demonstrating it was not found.

Following this approach, co-benefits in biodiversity are defined as any increases in alpha, beta, and/or gamma diversity as is described in the Convention on Biological Diversity[2]. Water ecosystem benefits include water regulation, water purification, and storm protection as defined in the Millennium Ecosystem Assessment (MEA, 2005). Soil-related benefits are characterized by improvement in metrics of soil quality that enhance productivity, maintain nutrient cycling, and improve plant growth (Shukla, Lal and Ebinger, 2006) as well as the improved potential food provision and reduced soil erosion services described in the Millennium Ecosystem Assessment. Air-related benefits are referred to as the “air quality regulation” ecosystem service described in the Millennium Ecosystem Assessment.

Notable efforts by TNC have focused on the cost-effectiveness of source water protection and **Water Funds** in the provision of climate and conservation co-benefits.


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On the water side, notable efforts by TNC have focused on the cost-effectiveness of source water protection and Water Funds in the provision of climate and conservation co-benefits. Source water protection has broad geographic relevance for reducing land-based sources of nonpoint pollution, raising the question of how to comparatively analyze locations around the world where it will yield better results. An analysis of return on investment in watersheds and cities around the world was performed as part of assessing enabling conditions for Water Funds worldwide. This analysis focused on estimation of potential water quality treatment savings (reduction in concentrations of sediments and Phosphorus) relative to conservation costs. This information was used to generate maps of “high-opportunity” watersheds and cities for investments in Nature-based Solutions for source water protection. Figure 1 shows preliminary results of this analysis. Detailed studies of Water Funds applications at global and local scales are documented in Abell *et al.* (2019), Kroeger *et al.* (2019) and Vogl *et al.* (2017).

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[2] United Nations. 1992. Convention on Biological Diversity. (also available at https://www.cbd.int/doc/legal/cbd-en.pdf).

FIGURE 1. HIGH OPPORTUNITY CITIES AND WATERSHED FOR INVESTMENTS IN NATURAL BASED SOLUTIONS FOR SOURCE WATER PROTECTION (SOURCE: TNC, 2018).

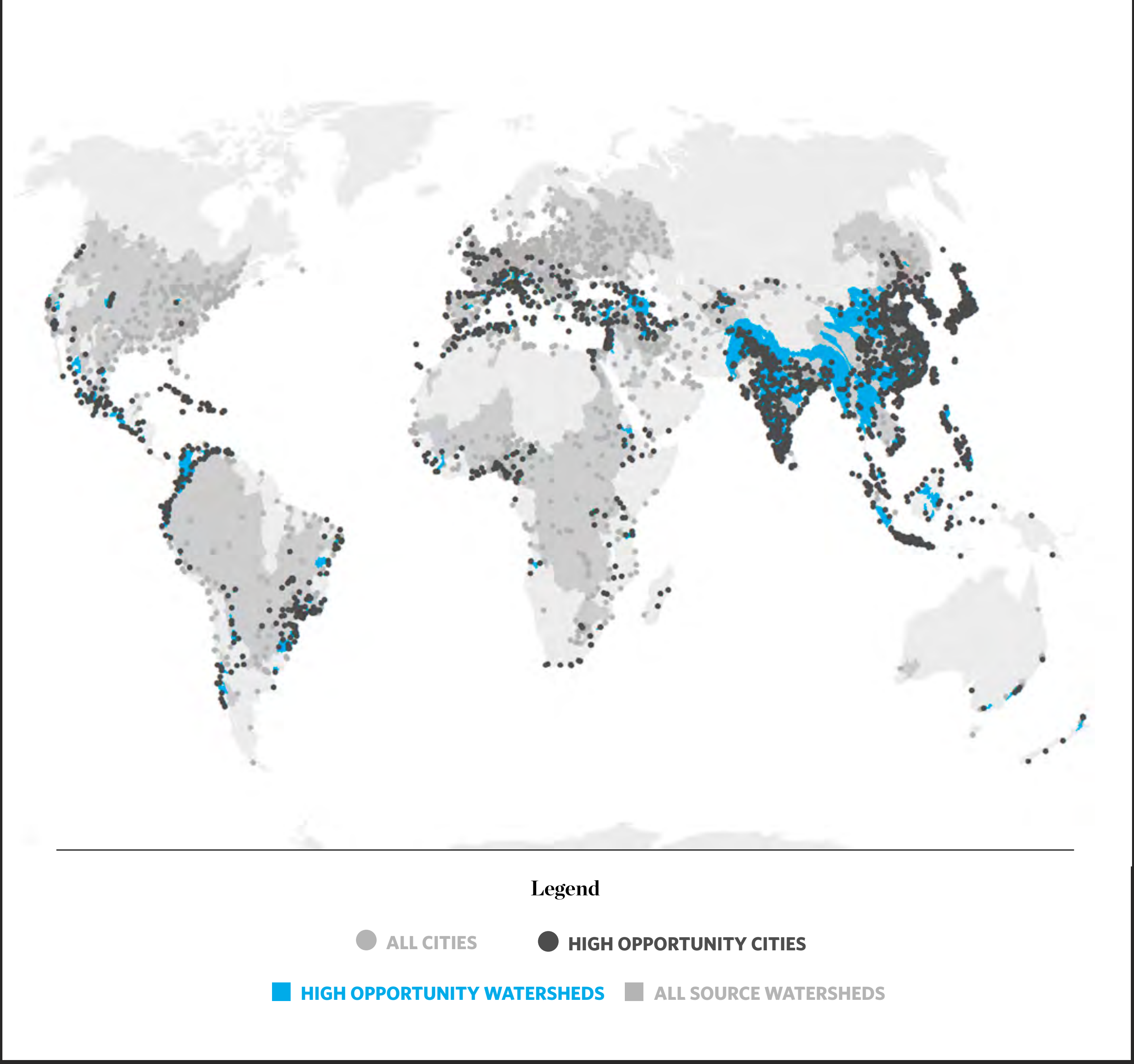

TABLE 3. CONSERVATION AND ADAPTATION CO-BENEFITS ASSOCIATED WITH NBS:

Summary of publications providing evidence that a given type of ecosystem service is enhanced due to implementation of an NbS. Cells in white indicate cases where there is no clear evidence of enhanced ecosystem services in the literature; adapted from (Griscom *et al.*, 2017), (FAO, 2019).

NbS	Biodiversity (alpha, beta, gamma)	Water (quantity, quality)	Soil (quality)	Air (quality)
FORESTS				
AVOIDED FOREST CONVERSION	Results indicate the irreplaceable value of continuous primary forests for conserving biodiversity (Sakai and Umetsu, 2014).	Improved availability of water for crop irrigation, drought mitigation; avoided sedimentation and water regulation for hydroelectric dams (Ferraro *et al.*, 2012)	Water retention and flow regulation (Jankowska-Huflejt, 2006). Maintains soil biological and physical properties ensuring health and productivity of forests (Jurgensen *et al.*, 1997)	Ozone abatement benefits of reforestation (Kroeger *et al.*, 2014). Multiple modeling studies describe health benefits of air filtration by forests (Nowak et al, 2013; Nowak et al, 2014)
REFORESTATION	Tree plantings can create wildlife corridors and buffer areas that enhance biological conservation (Harrison, Wardell-Johnson and McAlpine, 2003).	Improved availability of water for crop irrigation, drought mitigation; avoided sedimentation and water regulation for hydroelectric dams (Ferraro *et al.*, 2012)	Measured increase in soil fauna in reforested sites. During drought conditions earthworms only survived in reforested areas (Niijima and Yamane, 1991)	Ozone abatement benefits of reforestation (Kroeger *et al.*, 2014). Multiple modeling studies describe health benefits of air filtration by forests (Nowak et al, 2013; Nowak et al, 2014)
NATURAL FOREST MANAGEMENT	Species richness of invertebrates, amphibians, and mammals decreases as logging intensity increases (Burivalova, Şekercioğlu and Koh, 2014).	Harvesting that removes large proportions of biomass increases water flows and flooding thereby altering freshwater ecosystem integrity (Burton, 1997).	Timber harvesting that removes large amounts of woody debris reduces soil biological and physical properties thereby reducing health and productivity (Jurgensen *et al.*, 1997)	
IMPROVED PLANTATIONS	Forest plantations that consider community type such as polycultures over monocultures, native over exotics, disturbance pattern replication, longer rotations, and early thinning can enhance biodiversity (Hartley, 2002).			

NbS	Biodiversity (alpha, beta, gamma)	Water (quantity, quality)	Soil (quality)	Air (quality)
FORESTS				
FIRE MANAGEMENT	Fire management that mimics natural historic fire regimes can improve forest biodiversity (Bengtsson *et al.*, 2000).	Forests that survive fires (i.e. reduced catastrophic wild fires) contain more organic matter, improved soil properties, and lower recovery times enhance water infiltration and retention (Imeson *et al.*, 1992).	Forests that survive fires (i.e. reduced catastrophic wild fires) contain more organic matter, improved soil properties, and lower recovery times enhance water infiltration and retention (Nyman *et al.* 2015).	Possibility of small increases in mortality due to abrupt and dramatic increases in particulate matter concentrations from wildfire smoke (Vedal and Dutton, 2006)
AVOIDED WOODFUEL HARVEST	Woodfuel collection reduces saproxylic material used as food and habitat for forest organisms and fauna (Bouget, Lassauce and Jonsell, 2012).	Limiting soil compaction during woodfuel harvest reduces runoff and increases forest water retention (Bouget, Lassauce and Jonsell, 2012)	Fuel wood harvest causes soil compaction and disturbance that can change soil chemical properties (Bouget, Lassauce and Jonsell, 2012)	More efficient cook stoves improve indoor air quality and "reduce the incidence of mortality and disease" (Jeuland and Pattanayak, 2012; Bailis *et al.*, 2009; Smith *et al.*, 2000)
AGRICULTURE & GRASSLANDS				
AVOIDED GRASSLAND CONVERSION	Important habitat for nesting and foraging birds (Ausden, Sutherland and James, 2001).	Permanent grasslands provide "biological flood control" and maintain ecosystem water balance assuring adequate water resources.	Soil macroinvertebrates are important prey for breeding wading birds on lowland wet grassland (Jankowska-Huflejt, 2006).	
BIOCHAR			The addition of biochar enhances soil quality and fertility in temperate regions (Tenenbaum, 2009).	
CROPLAND NUTRIENT MANAGEMENT	Increased fish species richness and abundance. (Breitburg *et al.*, 2009)	Benefits associated with improved drinking water quality, increased opportunities for recreation, and health benefits (Smith *et al.*, 2013)	Better nutrient management maintains soil fertility (Smith *et al.*, 2013)	Precision management of soil nutrients can reduce ammonia and nitric oxide emissions (Smith *et al.*, 2013)
CONSERVATION AGRICULTURE	Agroforestry provides habitat for species and supports connectivity (Derpsch *et al.*, 2010)	Reduces agricultural water demands with appropriate cover crops (Derpsch *et al.*, 2010)	Reduces soil erosion and redistribution maintaining soil depth and water retention (Keeler *et al.*, 2012; Breitburg *et al.*, 2009)	

NbS	Biodiversity (alpha, beta, gamma)	Water (quantity, quality)	Soil (quality)	Air (quality)
AGRICULTURE & GRASSLANDS				
TREES IN CROPLANDS		Erosion control and water recharge (Jose, 2009; Patanayak and Mercer, 1998)	Decreased soil erosion (Jose, 2009; Patanayak and Mercer, 1998).	Tree planting helps capture airborne particles and pollutant gases (Jose, 2009; Patanayak and Mercer, 1998)
GRAZING - OPTIMAL INTENSITY	A gradient of intensive to extensively grazed pastures reduces overall disturbance to plant-insect interactions (Kruess and Tscharntke, 2002)	Nearly 70% of water use for cattle occurs during farm grazing, managed grazing practices can reduce water use on managed pastures (Rotz *et al.*, 2015)	Over grazing can reduce the soils ability to trap contaminants and cause a release of these and other suspended sediments (Keeler *et al.*, 2012; Breitburg *et al.*, 2009)	Erosion control and water recharge (151)(152)..
GRAZING - LEGUMES IN PASTURES	The presence of legumes in prairie leads to higher insect herbivore and insect predator diversity (Haddad *et al.*, 2009)		Legumes provide other ecological services including improved soil structure, erosion protection and greater biological diversity (Haddad *et al.*, 2009)	
IMPROVED RICE CULTIVATION		Alternating wet dry and midseason drainage of irrigated rice fields reduces water demands for agriculture (Jensen and Hauggaard-Nielsen, 2003). The use of gray water in agriculture can reduce gross water consumption (Sander, Wassmann and Siopongco, 2015; Faiz-ul Islam *et al.*, 2020).		
WETLANDS				
AVOIDED WETLAND IMPACTS	Maintains the provision of structure, nutrients and primary productivity and nurseries for commercially important fish and shrimp (Toze, 2006; Heumann, 2011; Duke *et al.*, 2007)	Coastal wetlands have an assessed economic value of $785-$34,700 in wastewater treatment value (Zedler and Kercher, 2005).	Benefits of cross-system nutrient transfer to coral reefs, coastal protection, and water quality regulation (Hemond and Benoit, 1988).	Tree planting helps capture airborne particles and pollutant gases (Smith *et al.*, 2013)

NbS	Biodiversity (alpha, beta, gamma)	Water (quantity, quality)	Soil (quality)	Air (quality)
WETLANDS				
AVOIDED PEATLAND IMPACTS	Boreal peat bogs contain distinctive insects in addition to widely distributed generalists (Duke *et al.*, 2007; Barbier *et al.*, 2011).	Peatlands and wetland soils attenuate flooding (Ming *et al.*, 2007)	Peatland clearing increases fire risk (Page *et al.*, 2002)	Exposure to pollutants from peat fires increases in the need for health services to treat lung and pulmonary disorders (Rappold *et al.*, 2011)
WETLANDS RESTORATION	Maintains the provision of structure, nutrients and primary productivity and nurseries for commercial fish and shrimp (Toze, 2006; Duke *et al.*, 2007; Heumann, 2011)	Flood control and water filtration benefits of mangroves (166) and other coastal wetlands (Duke *et al.*, 2007)	Benefits of cross-system nutrient transfer to coral reefs, coastal protection, and water quality regulation (Hemond and Benoit, 1988).	Tree planting helps capture airborne particles and pollutant gases (Smith *et al.*, 2013).
PEATLAND RESTORATION	Regeneration of peatlands reestablishes diverse communities (Chapman *et al.*, 2003)	Waste water treatment and storm water remediation (Das and Vincent, 2009; Rousseau *et al.*, 2008).	Restoring degraded lands to high productivity depend on faunal species that help develop soil structure and fertility (Lal and Stewart, 1992).	Rewetting peatlands reduces fire risk (Page *et al.*, 2009)

CLIMATE CHANGE MITIGATION CO-BENEFITS OF NBS

CHANGE AND CONSERVATION OF LAND, WATER, AND BIODIVERSITY CAPTURING AGRICULTURE NATURE-BASED SOLUTIONS FOR CLIMATE

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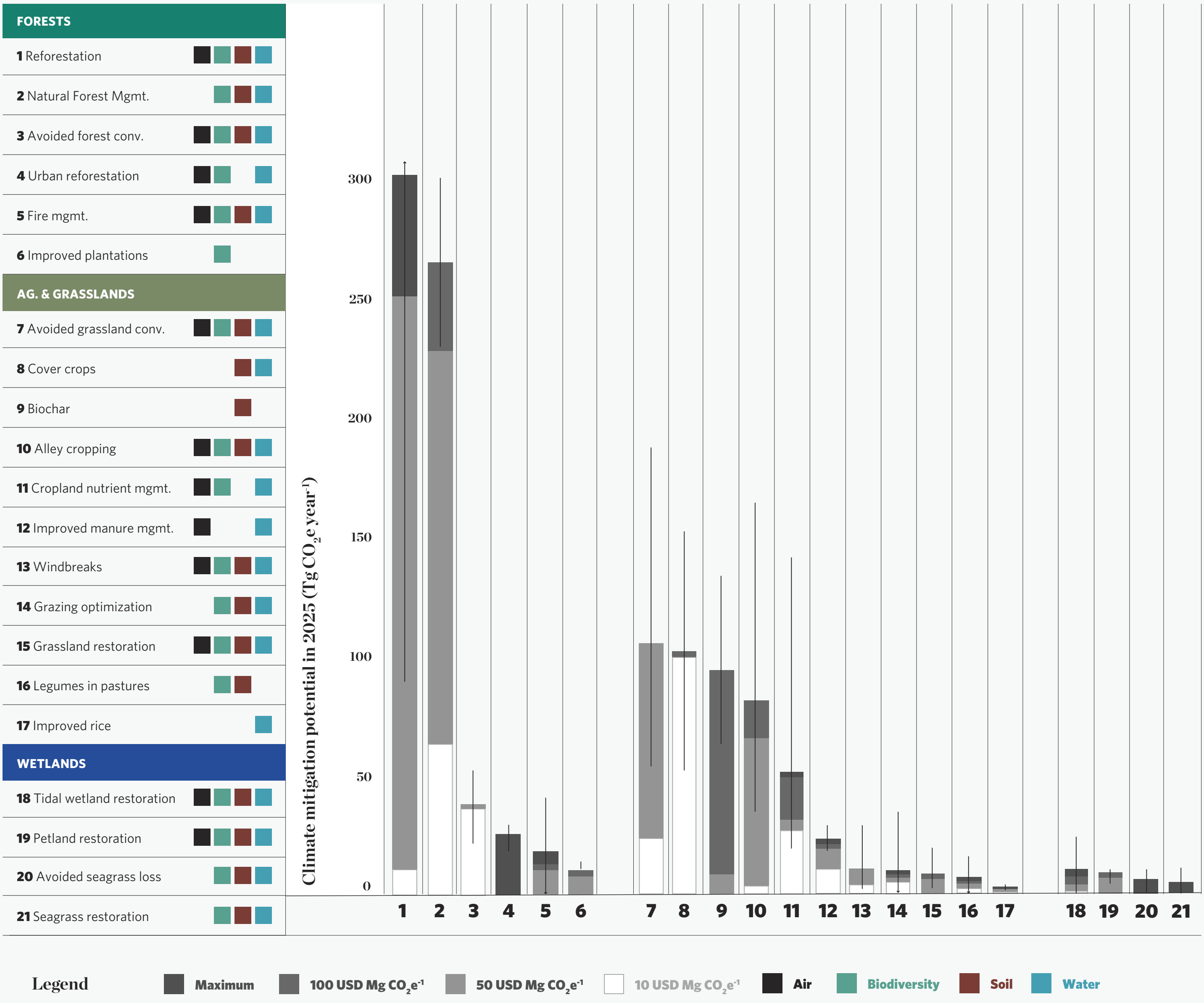
The intensity of global efforts towards mitigating the effects of climate change through reduction of emissions of greenhouse gases, and more recently through carbon sequestration, have resulted in an increased focus on NbS for climate mitigation. These global efforts have yielded a rich amount of literature that characterizes NbS in agricultural landscapes with mitigation in a much more specific and quantitative way relative to the conservation and adaptation co-benefits discussed above. This is in part due to the fact that climate mitigation has a clear global goal (e.g., limiting to 2 degrees the increase in mean global temperature) and that vast resources in research have been invested over the past 3 decades (e.g., IPCC, the World Climate Research Program, and other global, regional and national efforts).

FIGURE 2: . CLIMATE MITIGATION POTENTIAL OF NBS

Maximum climate mitigation potential with safeguards has been estimated for the reference year 2030. Dark-colored portions of bars represent cost-effective mitigation levels assuming a global ambition to hold warming to <2 °C (<100 USD $MgCO_2e^{-1}$ y^{-1}). Light-colored portions of bars indicate medium (<50 USD $MgCO_2e^{-1}$ y^{-1}) and low-cost (<10 USD $MgCO_2e^{-1}$ y^{-1}) portions of <2 °C levels. Wider error bars indicate empirical estimates of 95% confidence intervals, while narrower error bars indicate estimates derived from expert elicitation. Conservation co-benefits linked with each NbS are indicated by colored bars for biodiversity, water (quantity and quality), soil (quality), and air (quality). Asterisks indicate truncated error bars. Source: adapted from TNC's Lands of Opportunity (TNC, 2017).



A key literature source for the application of NbS to climate mitigation was co-produced by TNC (10). *Natural Climate Solutions* (TNC, 2020) provides an in-depth analysis of NbS for climate mitigation with a particular focus on agricultural landscapes and avoidance/ reduction of emissions through carbon sequestration. This peer-reviewed work provides an overall summary of the potential of NbS towards climate mitigation potential as 23.8 $PgCO_2e$ y^{-1} (95% CI 20.3–37.4) at a 2030 reference year (Table 4 and depicted in Figure 2). This estimate is not constrained by costs, but it is constrained by a global land cover scenario with safeguards for meeting increasing human needs for food and fiber. It also assumes no reduction in existing cropland area but does allow for grazing lands in forested ecoregions to be reforested, consistent with agricultural intensification and diet change scenarios. This potential value is also constrained by excluding activities that would either negatively impact biodiversity (e.g., replacing native non-forest ecosystems with forests) or have carbon benefits that are offset by net biophysical warming (e.g., albedo effects from expansion of boreal forests).

The analysis done in the Natural Climate Solutions effort and the research conducted therein includes the tradeoff between costs and benefits of NbS implementation for climate mitigation. This is approached through an analysis of published information on the fraction of maximum mitigation potential that offers a cost-effective contribution to meeting the Paris Climate Agreement goal of limiting warming to below 2 °C.

The fraction of NbS that are cost effective for holding warming to below 2 °C are informed by published marginal abatement cost (MAC) curves. Due to highly sparse and coarse spatial resolution data on costs of NbS for climate and conservation purposes, the reviewed literature was complemented by searching for MAC curves for each NbS; searches were also conducted searched for regional and local studies.

This limit of <2 °C is referenced in the literature as a cost-effective level of mitigation equivalent to a marginal abatement cost not greater than ~100 USD MgCO −1 as of 2030. This ensures that the marginal (per unit) cost of emissions reductions from NCS does not exceed the marginal benefit of avoiding carbon emissions. The marginal benefit of emissions reductions is represented by estimates of the social cost of carbon, which is the value to society of the avoided marginal damage of CO_2 emissions due to climate change and is obtained through welfare-maximizing emissions pricing models (Tol, 2005; Nordhaus, 2014). The social cost of carbon in 2030 is estimated to be 82-260 USD $MgCO_2e^{-1}$ to meet the 1.5-2°C climate target (Dietz and Stern, 2015).

This value is consistent with estimates for the avoided cost to society from holding warming to below 2 °C (Dietz and Stern, 2015; Canadell and Raupach, 2008; Meinhausen *et al.*, 2009). The 100 USD constrained estimate (11.3 PgCO2e y^{-1} in Table 4) is consistent with prior central estimates, chiefly with the upper-end estimate from the IPCC Fifth Assessment Report (AR5) (10.6 PgCO2e y^{-1}), and also with the values used in Griscom *et al.* (2017).

The proportion of climate mitigation towards a <2°C outcome that could be achieved at low cost was also assessed as part of this literature review. A marginal cost threshold of ~10 USD $MgCO2e^{-1}$ was used for this purpose, consistent with the current cost of emission reductions efforts underway and current prices on existing carbon markets.

The review of published data also reveals that more than one-third of the <2 °C cost effective levels for NbS are low cost (<10 USD $MgCO_2e^{-1}$, 4.1 $PgCO_2e$ y^{-1}; Figure 1 and Table 3). The "low-cost" and cost-effective" carbon sequestration opportunities compare favorably with cost estimates for emerging technologies, most notably bioenergy with carbon capture and storage (BECCS)—which range from ~40 USD MgCO −1 to over −1 21,000 USD per $MgCO_2$. Furthermore, large-scale BECCS is largely untested and likely to have significant impacts on water use, biodiversity, and other ecosystem services.

The marginal **benefit of emissions reductions** is represented by estimates of the social cost of carbon

TABLE 4. MAXIMUM MITIGATION POTENTIAL OF NBS BY 2030

Key literature sources used in estimating values are listed below each value. Mitigation potential given in million tons CO_2e per year (Tg CO_2e yr^{-1}). Negative Fluxes indicate carbon sequestration. Uncertainty values derived from ranges in literature sources; adapted from (Griscom *et al.*, 2017).

		Extent			Intensity			2030 BAU Flux	Time Horizon	Mitigation Potential	
	NbS	**Rate of avoidable impact** (Mha yr^{-1})	**Maximum potential extent of implementation** (units as noted)	**Extent Uncertainty 95% CI bounds** (units as noted)	**Avoidable Flux** (units as noted)	**Additional Sequestration** (MgC ha^{-1} yr^{-1})	**Flux Uncertainty 95% CI bounds** (units as noted)	**Baseline Flux in 2030** (TgCO2e yr^{-1})	**Years**	**Maximum Additional Mitigation Potential** (TgCO2e yr^{-1})	**Maximum Mitigation 95% CI bounds** (± TgCO2e yr^{-1})
AVOIDED FOREST CONVERSION	**Conversion of Natural Forests**	5.93			112.80 Mg ha^{-1}			-2,452	>100	2,452	
	References	(Tyukavina *et al.*, 2015)			(Tyukavina *et al.*, 2015) (Achard *et al.*, 2004) (Powers *et al.*, 2011)					(Tyukavina *et al.*, 2015) (Achard *et al.*, 2004) (Powers *et al.*, 2011)	
	Clearing for Subsistence Agriculture	3.04			103.29 Mg ha^{-1}			-1,151	>100	1,151	
	References	(Tyukavina *et al.*, 2015) (Hosonuma *et al.*, 2012)			(Tyukavina *et al.*, 2015) (Powers *et al.*, 2011)					(Tyukavina *et al.*, 2015) (Achard *et al.*, 2004)	
	All	0.97		7.95 - 9.98	109.58 Mg ha^{-1}		96 - 123	-3,603	>100	304	2,999 - 4,209
REFORESTATION	**Temperate**		206 Mha			2.82		202	>30	2,100	
	References		(Minnemeyer *et al.*, 2014) (Hansen *et al.*, 2013)			(IPCC, 2003) (Richards and Stokes, 2004) (Mokany, Raison, Prokushkin, 2006)		(Hansen *et al.*, 2013)			
	Tropical & subtropical		472 Mha			4.71		953	25	8,025	
	References		(Minnemeyer *et al.*, 2014) (Hansen *et al.*, 2013)			(Powers *et al.*, 2011) (Mokany, Raison, Prokushkin, 2006) (Bonner, Schmidt, Shoo, 2013)		(Hansen *et al.*, 2013)			
	All		678 Mha	230 - 1125		4.14	2.81 - 5.46	1,132	>25	10,124	2,727 - 17,867
NATURAL FOREST MANAGEMENT	**Temperate & Boreal**		1369 Mha			0.14		0	>50	690	
	References		(Brown and Birdsey, 1997)			(Roxburgh *et al.*, 2006) (Harmon and Marks, 2011) (FAO, 2015)					
	Tropical & subtropical		545 Mha			0.39		0	>50	780	
	References		(Brown and Birdsey, 1997)			(Putz *et al.*, 2012) (IPCC, 2006)					
	All		1914 Mha	1247 - 2350		0.21	0.18 - 1.20	0	>50	1,470	921 - 8,224

		Extent			Intensity			2030 BAU Flux	Time Horizon	Mitigation Potential	
	NbS	**Rate of avoidable impact** (Mha yr^{-1})	**Maximum potential extent of implementation** (units as noted)	**Extent Uncertainty 95% CI bounds** (units as noted)	**Avoidable Flux** (units as noted)	**Additional Sequestration** (MgC ha^{-1} yr^{-1})	**Flux Uncertainty 95% CI bounds** (units as noted)	**Baseline Flux in 2030** (TgCO2e yr^{-1})	**Years until saturation**	**Maximum Additional Mitigation Potential** (TgCO2e yr^{-1})	**Maximum Mitigation 95% CI bounds** (± TgCO2e yr^{-1})
IMPROVED PLANTATIONS	**Temperate & Boreal**		176 Mha	0.04 - 0.16	351.86 MgC ha^{-1}		268 - 436	-130	68	130	
	References		(Brown and Birdsey, 1997)		(Jardine and Siikamäki, 2014) (Donato *et al.*, 2011) (Pendleton *et al.*, 2012) (Siikamäki *et al.*, 2013) (Twilley, Chen, Hargis, 1992) (Bridgham *et al.*, 2006) (Laffoley *et al.*, 2009) (Murray, and Pendleton, 2013) (Hutchison *et al.*, 2014)						
	Tropical & Subtropical		81 Mha	0.10	142.78 MgC ha^{-1}		52 - 234	-42	64	42	
	References		(Brown and Birdsey, 1997)		(Pendleton *et al.*, 2012)						
	All		257 Mha		152.02 MgC ha^{-1}			-304	>64	304	141 - 466
FIRE MANAGEMENT	**Tropical Peatland**	0.46			11.13 Mg ha^{-1}			-77		19	7 - 182
	References	(Wiedinmyer and Hurteau, 2010) (Alencar, Nepstad, Diaz, 2006)								(Wiedinmyer and Hurteau, 2010) (Alencar, Nepstad, Diaz, 2006)	
	Temperate Peatland	0.54			34.34 Mg ha^{-1}			-68		68	17 - 117
	References	(Anderson *et al.*, 2015)								(Anderson *et al.*, 2015)	
	Boreal Peatland	not applicable			not applicable					125	50 - 200
	References									(van der Werf *et al.*, 2010)	
	All							-145	>100	212	166 - 411
AVOIDED WOODFUEL HARVEST	**All**		2,800 M people		0.04 MgC person^{-1} yr^{-1}			-748	>100	367	326 - 407
	References		(Ramankutty and Foley, 1999)						(Tyukavina *et al.*, 2015) (Ramankutty and Foley, 1999)		
Forest Subtotal										16,219	11,291 - 28,133

		Extent			Intensity			2030 BAU Flux	Time Horizon	Mitigation Potential	
	NbS	**Rate of avoidable impact** (Mha yr^{-1})	**Maximum potential extent of implementation** (units as noted)	**Extent Uncertainty 95% CI bounds** (units as noted)	**Avoidable Flux** (units as noted)	**Additional Sequestration** (MgC ha^{-1} yr^{-1})	**Flux Uncertainty 95% CI bounds** (units as noted)	**Baseline Flux in 2030** (TgCO2e yr^{-1})	**Years**	**Maximum Additional Mitigation Potential** (TgCO2e yr^{-1})	**Maximum Mitigation 95% CI bounds** (± TgCO2e yr^{-1})
AVOIDED GRASSLAND CONVERSION	**Temperate**	0.70			18.40 Mg ha^{-1}			-47	>100	47	
	References	(Jobbágy and Jackson, 2000)			(Putz *et al.*, 2012) (Slade, Bauen and Gross, 2014) (Slade and UKERC, 2011)						
	Tropical & subtropical	1.00			18.80 Mg ha^{-1}			-69	>100	69	
	References	(Jobbágy and Jackson, 2000)			(Davidson and Ackerman, 1993) (Slade, Bauen and Gross, 2014)						
	All	0.97		1.13 - 5.40	18.65 Mg ha^{-1}		15.91 - 21.39	-116	>100	116	75 - 373
BOCHAR	**All**		1,670 Tg dm yr^{-1}	939 - 2075		0.18 MgCe (Mg dm)$^{-1}$	0.17 - 0.21	0	>100	1,102	642 - 1,455
	References		(Spokas, 2010)			(Herath *et al.*, 2015) (Meyer, Glaser, Quicker, 2011) (Dharmakeerthi *et al.*, 2015) (Liang *et al.*, 2008)					
CROPLAND NUTRIENT MANAGEMENT	**All**		44 Tg N yr^{-1} used	32.6 - 58.0	4.33 MgCe Mg N^{-1}		2.9 - 5.3	-2612	>100	706	
	References		(Bodirsky *et al.*, 2014)					(Oenema *et al.*, 2014)		(Oenema *et al.*, 2014) (Mueller *et al.*, 2014) (Davidson, 2009) (Snyder *et al.*, 2009)	399 - 959
CONSERVATION AGRICULTURE	**All**		352 Mha			0.32		28	>50	413	310 - 516
	References		(Poeplau and Don, 2015) (Trabucco *et al.*, 2008)			(Trabucco *et al.*, 2008)		(Trabucco *et al.*, 2008)	(Trabucco *et al.*, 2008)	(Trabucco *et al.*, 2008)	
TREES IN CROPLANDS	**Windbreaks**		318 Mha	70.4 - 400		0.20		0	50	204	
	References		(Kumar and Nair, 2011) (Chendev *et al.*, 2014)			(Wang *et al.*, 2013) (Sauer, Cambardella, Brandle, 2007) (Dhillon and Rees, 2017) (Schoeneberger, 2008) (Kort and Turnock, 1998)					
	Alley cropping		140 Mha	48.8 - 205		1.20		0	50	616	
	References		(Chendev *et al.*, 2014)			(Nair, Kumar, Nair, 2009) (Cardinal *et al.*, 2012) (Tsonkova *et al.*, 2012) (Lu *et al.*, 2015) (Oelbermann *et al.*, 2006) (Peichl *et al.*, 2006) (Bambrick *et al.*, 2010)					
	Farmer Managed Natural Regen		150 Mha	35.0 - 388		0.40	0.22 - 0.76	0	50	220	469 - 1,855
	References		(Searchinger *et al.*, 2018) (Luedeling and Neufeldt, 2012)			(Henderson *et al.*, 2015)			(Luedeling and Neufeldt, 2012)		
	All		608 Mha			0.37		0	50	1,040	

		Extent			Intensity			2030 BAU Flux	Time Horizon	Mitigation Potential	
NbS		**Rate of avoidable impact** (Mha yr^{-1})	**Maximum potential extent of implementation** (units as noted)	**Extent Uncertainty 95% CI bounds** (units as noted)	**Avoidable Flux** (units as noted)	**Additional Sequestration** (MgC ha^{-1} yr^{-1})	**Flux Uncertainty 95% CI bounds** (units as noted)	**Baseline Flux in 2030** (TgCO2e yr^{-1})	**Years until saturation**	**Maximum Additional Mitigation Potential** (TgCO2e yr^{-1})	**Maximum Mitigation 95% CI bounds** (± TgCO2e yr^{-1})
GRAZING - OPTIMAL INTENSITY	**All**		712 Mha			0.06	268 - 436	0	>100	148	148 - 699
	References		(Henderson *et al.*, 2015)			(Henderson *et al.*, 2015)				(Henderson *et al.*, 2015)	
GRAZING - LEGUMES IN PASTURES	**All**		72 Mha			0.56	52 - 234	0	>100	147	14 - 1,500
	References		(Henderson *et al.*, 2015)			(Henderson *et al.*, 2015)					
FIRE MANAGEMENT	**All**		1,400 M head cattle			0.13 MgCe head^{-1}		-2,412	>100	680	35 - 1,014
	References		(FAO, 2012)			(Thornton and Herrero, 2010)		(Thornton and Herrero, 2010)		(Thornton and Herrero, 2010)	
GRAZING - IMPROVED FEED	**All**		1,400 M head cattle		0.04 MgCe head^{-1}			-2,412	>100	200	75 - 214
	References		(FAO, 2012)		(Thornton and Herrero, 2010)					(Thornton and Herrero, 2010)	
IMPROVED RICE CULTIVATION	**All**		163 Mha		0.44 MgCe ha^{-1} yr^{-1}			-755	>100	265	227 - 319
	References		(US EPA, 2016)		(US EPA, 2016) (Golub *et al.*, 2009)			(US EPA, 2016)			
Agriculture & Grasslands Subtotal										4,817	4,398 - 6,926

		Extent			Intensity			2030 BAU Flux	Time Horizon	Mitigation Potential	
	NbS	**Rate of avoidable impact** (Mha yr^{-1})	**Maximum potential extent of impact** (units as noted)	**Extent Uncertainty 95% CI bounds** (units as noted)	**Avoidable Flux** (units as noted)	**Additional Sequestration** (MgC ha^{-1} yr^{-1})	**Flux Uncertainty 95% CI bounds** (units as noted)	**Baseline Flux in 2030** (TgCO2e yr^{-1})	**Years**	**Maximum Additional Mitigation Potential** (TgCO2e yr^{-1})	**Maximum Mitigation 95% CI bounds** (± TgCO2e yr^{-1})
AVOIDED WETLAND IMPACTS	**Mangrove**	0.10		0.04 - 0.16	351.86 MgC ha^{-1}		268 - 436	-130	68	130	
	References	(Macreadie *et al.*, 2017) (Siikamäki, Sanchirico, Jardine, 2012)			(Jardine and Siikamäki, 2014) (Donato *et al.*, 2011) (Pendleton *et al.*, 2012) (Siikamäki *et al.*, 2013) (Twilley, Chen, Hargis, 1992) (Bridgham *et al.*, 2006) (Laffoley *et al.*, 2009) (Murray, and Pendleton, 2013) (Hutchison *et al.*, 2014)						
	Salt Marsh	0.10		0.04 - 0.12	142.78 MgC ha^{-1}		52 - 234	-42	64	42	
	References	(Pendleton *et al.*, 2012)			(Pendleton *et al.*, 2012)						
	Seagrass	0.45		0.12 - 0.78	79.95 MgC ha^{-1}		27-133	-132	67	132	
	References	(Pendleton *et al.*, 2012)			(Pendleton *et al.*, 2012) (Fourqurean *et al.*, 2012)						
	All	0.63			152.02 MgC ha^{-1}			-304	>64	304	141 - 466
PEATLAND RESTORATION	**Tropical Peatland**	0.57			317.54 MgCe ha^{-1}			-664	89	664	
	References	(Tapio-Biström *et al.*, 2012)			(Tapio-Biström *et al.*, 2012) (Murdiyarso, Hergoualc'h, Verchot, 2010)						
	Temperate Peatland	0.14			146.08 MgCe ha^{-1}			-75	>100	75	
	References	(Tapio-Biström *et al.*, 2012)			(Tapio-Biström *et al.*, 2012) (Adams and Faure, 1998)						
	Boreal Peatland	0.07			59.20 MgCe ha^{-1}			-15	>100	15	
	References	(Tapio-Biström *et al.*, 2012)			(Tapio-Biström *et al.*, 2012) (Adams and Faure, 1998)						
	All	0.78			266.68 MgCe ha^{-1}		197-550	-754	-89	754	237-1,212

		Extent			Intensity			2030 BAU Flux	Time Horizon	Mitigation Potential	
	NbS	**Rate of avoidable impact** (Mha yr^{-1})	**Maximum potential extent of implementation** (units as noted)	**Extent Uncertainty 95% CI bounds** (units as noted)	**Avoidable Flux** (units as noted)	**Additional Sequestration** (MgC ha^{-1} yr^{-1})	**Flux Uncertainty 95% CI bounds** (units as noted)	**Baseline Flux in 2030** (TgCO2e yr^{-1})	**Years**	**Maximum Additional Mitigation Potential** (TgCO2e yr^{-1})	**Maximum Mitigation 95% CI bounds** (± TgCO2e yr^{-1})
WETLAND IMPACTS	**Mangrove**		11 Mha	9 - 13	8.80 MgCe ha^{-1} yr^{-1}	6.4	12.0 - 18.4	-345	>100	596	
	References		(Mcleod *et al.*, 2011) (Macreadie *et al.*, 2019)		(Jardine and Siikamäki, 2014 (Hutchison *et al.*, 2014)	Mcleod *et al.*, 2011)					
	Salt Marsh		2 Mha	0.2 - 3.2	3.57 MgCe ha^{-1} yr^{-1}	2.2	3.43 - 8.07	-22	57	36	
	References		Mcleod *et al.*, 2011)		(Pendleton *et al.*, 2012)	Mcleod *et al.*, 2011)					
	Seagrass		17 Mha	8.3 - 25.4	2.00 MgCe ha^{-1} yr^{-1}	1.4	1.87 - 4.89	-124	51	209	
	References		Mcleod *et al.*, 2011)		(Pendleton *et al.*, 2012) (Fourqurean *et al.*, 2012)	(Bouillon *et al.*, 2008)					
	All		29 Mha		4.71 MgCe ha^{-1} yr^{-1}	3.3		-491	>51	841	621 - 1,064
PEATLAND RESTORATION	**Tropical Peatland**		17 Mha		7.94 MgCe ha^{-1} yr^{-1}			-497	20	497	642 - 1,455
	References		(Tapio-Biström *et al.*, 2012)		(Tapio-Biström *et al.*, 2012) (Murdiyarso, Hergoualc'h, Verchot, 2010)	(Bridgham *et al.*, 2014) (Mitsch, *et al.*, 2013) (Neubauer, 2014)					
	Temperate Peatland		20 Mha		3.65 MgCe ha^{-1} yr^{-1}	0.0		-267	20	267	
	References		(Tapio-Biström *et al.*, 2012)		(Tapio-Biström *et al.*, 2012) (Adams and Faure, 1998)	(Bridgham *et al.*, 2014) (Mitsch, *et al.*, 2013) (Neubauer, 2014)					
	Boreal Peatland		9 Mha		1.48 MgCe ha^{-1} yr^{-1}	0.0		-51	20	51	
	References		(Tapio-Biström *et al.*, 2012)		(Tapio-Biström *et al.*, 2012) (Adams and Faure, 1998)	(Bridgham *et al.*, 2014) (Mitsch, *et al.*, 2013) (Neubauer, 2014)					
	All		46 Mha		4.79 MgCe ha^{-1} yr^{-1}	0.0	3.5 - 9.9	-815	20	815	705 - 2,471
Wetlands Subtotal										2,713	2,415-4,502
Total NbS										**23,750**	**20,261-37,403**

TABLE 5. COST-EFFECTIVE AND LOW-COST MITIGATION LEVELS PROVIDED BY NBS

Literature sources used in setting both the Cost-Effective (100 USD/$MgCO_2e$; <2°C) and Low Cost (10 USD/$MgCO_2e$). See Table 4 for key sources used for estimating maximum additional mitigation potential; adapted from (Griscom *et al.*, 2017).

		Mitigation Potential					
	NbS	**Maximum Additional Mitigation Potential** (TgCO2e yr^{-1})	**Maximum Mitigation 95% CI bounds** (TgCO2e yr^{-1})	**Cost-Effective** (% of max)	**Cost-Effective** (TgCO2e yr^{-1})	**Low-Cost** (% of max)	**Low-Cost** (TgCO2e yr^{-1})
AVOIDED FOREST CONVERSION	**Conversion of Natural Forests**	2,452		90%	2206	60%	1,471
	References			(Kindermann, 2008) (Lubowski and Rose, 2013)		(Kindermann, 2008) (Lubowski and Rose, 2013)	
	Clearing for Subsistence Agriculture	1,151		60%	691	30%	345
	References						
	All	3,603	2,999 - 4,209	80%	2,897	50%	1,816
REFORESTATION	**Temperate**	2,100					
	References						
	Tropical & subtropical	8,025					
	References						
	All	10,124	2,727 - 17,867	30%	3,037	0%	0
	References			(Strengers, Van Minnen, Jeickhout, 2008)		(Strengers, Van Minnen, Jeickhout, 2008)	
NATURAL FOREST MANAGEMENT	**Temperate & Boreal**	690					
	References						
	Tropical & subtropical	780					
	References						
	All	1,470	921 - 8,224	60%	882	30%	441
	References			(Metz and IPCC, 2007) (IPCC and Edenhofer, 2014)		(Golub *et al.*, 2009) (IPCC and Edenhofer, 2014)	

	NbS	Mitigation Potential					
		Maximum Additional Mitigation Potential (TgCO2e yr^{-1})	**Maximum Mitigation 95% CI bounds** (TgCO2e yr^{-1})	**Cost-Effective** (% of max)	**Cost-Effective** (TgCO2e yr^{-1})	**Low-Cost** (% of max)	**Low-Cost** (TgCO2e yr^{-1})
IMPROVED PLANTATIONS	**Temperate & Boreal**	304					
	References						
	Tropical & subtropical	139					
	References						
	All	443	168 - 1,009	60%	266	0%	0
	References			(Golub *et al.*, 2009) (IPCC and Edenhofer, 2014)		(Golub *et al.*, 2009) (IPCC and Edenhofer, 2014)	
FIRE MANAGEMENT	**Temperate Fire Prone Forests**	19	7 - 182				
	References						
	Brazilian Amazon Forests	68	17 - 117				
	References						
	Global Savannas	125	50 - 200				
	References						
	All	212	166 - 411	60%	127	0%	0
	References						
AVOIDED WOODFUEL HARVEST	**All**	367	326 - 407	30%	110	0%	0
	References						
Forest Subtotal		16,219	11,291 - 28,133		7,320		2,257

		Mitigation Potential					
	NbS	**Maximum Additional Mitigation Potential** (TgCO2e yr^{-1})	**Maximum Mitigation 95% CI bounds** (TgCO2e yr^{-1})	**Cost-Effective** (% of max)	**Cost-Effective** (TgCO2e yr^{-1})	**Low-Cost** (% of max)	**Low-Cost** (TgCO2e yr^{-1})
AVOIDED GRASSLAND CONVERSION	**Temperate**	47					
	References						
	Tropical & subtropical	69					
	References						
	All	116	75 - 373	30%	35	0%	0
BIOCHAR	**All**	1,102	642 - 1,455	30%	331	0%	0
	References						
CROPLAND NUTRIENT MANAGEMENT	**All**	706	399 - 959	90%	635	90%	635
	References						
CONSERVATION AGRICULTURE	**All**	413	310 - 516	90%	372	60%	248
	References			(IPCC and Edenhofer, 2014)		(IPCC and Edenhofer, 2014)	
TREES IN CROPLANDS	**Windbreaks**	204		60%	122	0%	
	References						
	Alleycropping	616		30%	185	0%	
	References						
	Farmer Managed Natural Regen.	220		60%	135	0%	
	References						
	All	1,040	469 - 1,855	42%	439	0%	0
	References			(IPCC and Edenhofer, 2014)		(IPCC and Edenhofer, 2014)	

NbS		Mitigation Potential					
		Maximum Additional Mitigation Potential (TgCO2e yr^{-1})	**Maximum Mitigation 95% CI bounds** (TgCO2e yr^{-1})	**Cost-Effective** (% of max)	**Cost-Effective** (TgCO2e yr^{-1})	**Low-Cost** (% of max)	**Low-Cost** (TgCO2e yr^{-1})
GRAZING - OPTIMAL INTENSITY	**All**	148	148 - 699	60%	89	30%	45
	References			(Thornton and Herrero, 2010)		(Thornton and Herrero, 2010)	
GRAZING - LEGUMES IN PASTURES	**All**	147	14 - 1500	90%	132	60%	88
	References			(Thornton and Herrero, 2010)		(Thornton and Herrero, 2010)	
GRAZING - IMPROVED FEED	**All**	680	35 - 1014	30%	204	0%	0
	References			(Thornton and Herrero, 2010)		(Thornton and Herrero, 2010)	
GRAZING - ANIMAL MANAGEMENT	**All**	200	75 - 214	30%	60	0%	0
	References						
IMPROVED RICE CULTIVATION	**All**	265	227 - 319	60%	159	30%	80
	References			(Golub *et al.*, 2009) (IPCC and Edenhofer, 2014) (Beach *et al.*, 2015) (US EPA, 2015)		(Golub *et al.*, 2009) (IPCC and Edenhofer, 2014) (Beach *et al.*, 2015) (US EPA, 2015)	
Agriculture & Grasslands Subtotal		4,817	4,398 - 6,926	51%	2,456	23%	1,095

		Mitigation Potential					
	NbS	**Maximum Additional Mitigation Potential** (TgCO2e yr^{-1})	**Maximum Mitigation 95% CI bounds** (TgCO2e yr^{-1})	**Cost-Effective** (% of max)	**Cost-Effective** (TgCO2e yr^{-1})	**Low-Cost** (% of max)	**Low-Cost** (TgCO2e yr^{-1})
AVOIDED COASTAL WETLAND IMPACTS	**Mangrove**	130		90%	117	60%	78
	References						
	Salt Marsh	42		90%	38	60%	25
	References						
	Seagrass	132		90%	119	60%	79
	References						
	All	304	141 - 466	90%	273	60%	182
AVOIDED PEATLAND IMPACTS	**Tropical Peatland**	664					
	References						
	Temperate Peatland	75					
	References						
	Boreal Peatland	15					
	References						
	All	754	237 - 1,212	90%	678	60%	452
	References			(Siikamäki, Sanchirico, Jardine, 2012)		(Siikamäki, Sanchirico, Jardine, 2012)	
COASTAL WETLAND RESTORATION	**Mangrove**	596		30%	179	0%	0
	References						
	Salt Marsh	36		60%	22	0%	0
	References						
	Seagrass	209		0%	0	0%	0
	References						
	All	841	621 - 1,064	24%	200	0%	0
	References			(Bayraktarov *et al.*, 2016)		(Bayraktarov *et al.*, 2016)	

		Mitigation Potential					
	NbS	**Maximum Additional Mitigation Potential** (TgCO2e yr^{-1})	**Maximum Mitigation 95% CI bounds** (TgCO2e yr^{-1})	**Cost-Effective** (% of max)	**Cost-Effective** (TgCO2e yr^{-1})	**Low-Cost** (% of max)	**Low-Cost** (TgCO2e yr^{-1})
PEATLAND RESTORATION	**Tropical Peatland**	497		60%	298	30%	149
	References						
	Temperate Peatland	267		30%	80	0%	0
	References			(Schleupner and Schneider, 2013)		(Schleupner and Schneider, 2013)	
	Boreal Peatland	51		30%	15	0%	0
	References						
	All	815	705 - 2,471	48%	394	18%	149
	References					(IPCC and Edenhofer, 2014)	
Wetlands Subtotal		2,713	2,415 - 4,502	57%	1,546	29%	784
Total		**23,750**	**20,261 - 37,409**	**48%**	**11,321**	**17%**	**4,136**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Natural climate solutions such as NbS are thus particularly important in the near term for our transition to a **carbon-neutral economy** by the middle of this century.

Summarizing the contents of Table 4 and Table 5, projection estimates suggest that global warming can be held to below 2 °C if NbS pathways are implemented at cost-effective levels indicated in Table 5 and if increases in fossil fuel emissions are avoided for 10 years and then driven to 7% of current levels by 2050 and then to zero by 2095. This assumes a 10-year linear increase of NbS implementation to the cost-effective mitigation levels and a >66% likelihood of holding warming to below 2 °C following a model by Meinshausen *et al.* (176). NbS can provide 37% of the necessary climate mitigation between now and 2030 and 20% between now and 2050. Thereafter, the proportion of total mitigation provided further declines as the proportion of necessary avoided fossil fuel emissions increases and as some natural pathways saturate. Natural climate solutions such as NbS are thus particularly important in the near term for our transition to a carbon-neutral economy by the middle of this century.

Half of this cost-effective mitigation is due to additional carbon sequestration of 5.6 $PgCO_2e$ y^{-1} by nine of the NbS pathways, while the remainder is from pathways that avoid further emissions of CO_2, CH_4, and N_2O. Aggregate sequestration levels begin to taper off around 2060, although most pathways can maintain the 2030 mitigation levels reported here for more than 50 years and pathway-specific time horizons for saturation in Table 2). The aggregate NbS pathway illustrated in Figure 3 (10). will require substantial near-term ratcheting up of both fossil fuel and mitigation targets by countries to achieve the Paris Climate Agreement goal to hold warming to below 2 °C. Countries provided nationally determined contributions (NDCs) with 2025 or 2030 emissions targets as a part of the Paris Climate Agreement. While most NDCs indicate the inclusion of land sector mitigation, only 38 specify land sector mitigation contributions, of 160 NDCs assessed (Forsell *et al.*, 2016). Despite these limitations, analyses indicate that if NDCs were fully implemented, NCS would contribute about 20% of climate mitigation and about 2 $PgCO_2e$ y−1 mitigation by 2030. As such, a small portion of the 11.3 $PgCO_2e$ y^{-1} NCS opportunity we report here has been included in existing NDCs. Across all sectors, the NDCs fall short by 11–14 $PgCO_2e$ y^{-1} of mitigation needed to keep 2030 emissions in line with cost-optimal 2 °C scenarios (Rogelj *et al.*, 2016). Hence, NbS could contribute a large portion (about 9 $PgCO_2e$ y^{-1}) of the increased ambition needed by NDCs to achieve the Paris Climate Agreement.

Forest pathways offer over two-thirds of cost-effective mitigation needed to hold warming to below 2 °C and about half of the low-cost mitigation opportunities (Table 3). Reforestation is the largest natural pathway and deserves more attention to identify low-cost mitigation opportunities. Reforestation may involve trade-offs with alternative land uses, can incur high costs of establishment, and is more expensive than Avoided Forest Conversion. However, this conclusion from available MAC curves ignores opportunities to reduce costs, such as involving the private sector in reforestation activities by establishing plantations for an initial commercial harvest to facilitate natural and assisted forest regeneration. The high uncertainty of maximum reforestation mitigation potential is due to the large range in existing constrained estimates of potential reforestation extent. As with most forest pathways, reforestation has well-demonstrated co-benefits, including biodiversity habitat, air filtration, water filtration, flood control, and enhanced soil fertility (Table 4).

Avoided Forest Conversion offers the second-largest maximum and cost-effective mitigation potential. However, implementation costs may be secondary to public policy challenges in frontier landscapes lacking clear land tenure. The relative success of Brazil's efforts to slow deforestation through a strong regulatory framework, accurate and transparent federal monitoring, and supply chain interventions provides a promising model, despite recent setbacks. Relatively low uncertainty is found for Avoided Forest Conversion, reflecting considerable global forest monitoring research in the last decade stimulated by interest in reducing emissions from deforestation and forest degradation (REDD).

Improved forest management (i.e., Natural Forest Management and Improved Plantations pathways) offers large and cost-effective mitigation opportunities, many of which could be implemented rapidly without changes in land use or tenure. While some activities can be implemented without reducing wood yield (e.g., reduced-impact logging), other activities (e.g., extended harvest cycles) would result in reduced near-term yields. This shortfall can be met by implementing the Reforestation pathway, which includes new commercial plantations. The Improved Plantations pathway ultimately increases wood yields by extending rotation lengths from the optimum for economic profits to the optimum for wood yield. Grassland and agriculture pathways offer one-fifth of the total mitigation needed to hold warming below 2 °C while maintaining or increasing food production and soil fertility. Collectively, the grassland and agriculture pathways offer one-quarter of low-cost mitigation opportunities. Cropland Nutrient Management is the largest cost-effective agricultural pathway, followed by Trees in Croplands and Conservation Agriculture. Nutrient Management and Trees in Croplands also improve air quality, water quality, and provide habitat for biodiversity (Table 3). Recent literature reviewed here on nutrient management improves upon that presented


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Reforestation is the **largest natural pathway** and deserves more attention to identify low-cost mitigation opportunities.

by the IPCC AR5 in that it is informed by more recent data for fertilizer use and projections of future use of fertilizers. Future remote sensing analyses to improve the detection of low-density trees in croplands will constrain the uncertainty about the extent of this climate mitigation opportunity.

The addition of biochar to soil offers the largest maximum mitigation potential among agricultural pathways, but unlike most other NbS options, it has not been well demonstrated beyond research settings. Hence trade-offs, cost, and feasibility of large-scale implementation of biochar are poorly understood. From the livestock sector, two improved grazing pathways (Optimal Intensity and Legumes) increase soil carbon, while two others (Improved Feed and Animal Management) reduce methane emissions.

Wetland pathways offer considerable (~14 percent) mitigation opportunities needed to hold warming to <2 °C, and 19 percent of low-cost mitigation. Wetlands are less extensive than forests and grasslands, yet per unit area, they hold the highest carbon stocks and the highest delivery of hydrologic ecosystem services, including climate resilience. Avoiding the loss of wetlands (an urgent concern in developing countries) tends to be less expensive than wetland restoration. Improved mapping of global wetlands (particularly peatlands) is a priority for both reducing our reported uncertainty and for their conservation and restoration.

CONCLUDING REMARKS

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The extent to which NbS can contribute to agricultural production, conservation climate and socioeconomic co-benefits in agricultural landscapes is explored in this document through a literature review. Peer-reviewed literature sources on NbS with a global focus were found to abundant on benefits tackling climate mitigation (i.e., reduction of emissions and carbon sequestration). Literature sources on NbS applied to climate adaptation, conservation of land, water and biodiversity, and other ecosystem services and co-benefits were found to occur in lesser numbers and more localized geographically; place-based case study applications are generally found in the literature for these benefits. This is to be expected given the intense focus on the science of climate change globally and the maturity of efforts centered on mitigation sponsored by UNFCCC (e.g., IPCC, Green Climate Fund) and other global and regional organizations (e.g., World Bank Group, regional development banks). Because of this asymmetry in available published work, this literature review has been structured by separately grouping the co-benefits provided by NbS into: (i) agricultural production; (ii) conservation (biodiversity, land, water); (iii) climate (primarily mitigation, but also adaptation) and (iv) other (e.g., environmental, socioeconomic) applications of NbS in agricultural landscapes. Synergies across multiple co-benefits has been noted in some of the literature reviewed; this occurs particularly in the climate-related references, which often encompass conservation and other co-benefits.

Advancing implementation of NbS for climate and conservation purposes needs to emphasize gains in agricultural production and socioeconomic benefits to food producers this is an area of opportunity for future

> Advancing implementation of NbS for climate and conservation purposes needs to emphasize **gains in agricultural production and socioeconomic benefits to farmers**


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analytical work on the general topic of NbS. With the exception of a limited number of sources exist in the literature that are largely focused on local case study applications, e.g., (Current and Scherr, 1995; Grieg-Gran, Porras and Wunder, 2005; Pascual *et al.*, 2010; Zheng *et al.*, 2013; Hegde and Bull, 2011; Corbera, Kosoy and Martínez Tuna, 2007; Turpie, Marais and Blignaut, 2008), most published studies that are included in this literature review have stopped short of doing the economic analysis of NbS benefits (outside of climate and conservation, which have been done by the climate and conservation science communities rather than the agricultural science one). However, the analysis could be done to make estimates of these gains and benefits at a global scale of NbS implementation. Given the conservation and adaptation benefits documented for NbS, it is likely that economic benefits to food producers would be realized by NbS implementation, and further work would systematically quantify them.

The conjunctive realization of multiple co-benefits through the implementation of NbS in agricultural landscapes is an area of active research and experimentation in the field; a myriad of new approaches continues to be investigated and tested. For instance, recent research reviewed in Backer *et al.* (2018) has demonstrated that inoculating plants with plant-growth promoting rhizobacteria (PGPR) can be an effective strategy to stimulate crop growth. Furthermore, these strategies can improve crop tolerance for the abiotic stresses (e.g., drought, heat, and salinity) likely to become more frequent as climate change conditions continue to develop. This discovery has resulted in multifunctional PGPR-based formulations for commercial agriculture, to minimize the use of synthetic fertilizers and agrochemicals.

Another example that has been receiving increased attention lately is ecosystem services provided by insects. Examples include not only pollination, but also other services such as dung burial, pest control, and wildlife nutrition. A recent review of the value of ecosystem services provided by insects provides estimations of the value of each service on projections of losses that would accrue if insects were not functioning at their current level (Losey and Vaughan, 2006). This review estimates the annual value of these ecological services provided in the United States to be at least $57 billion, an amount that justifies greater investment in the conservation of these services.

Much contemporary **bioprospecting has multiple goals,** including the conservation of biodiversity, the sustainable management of natural resources and economic development.


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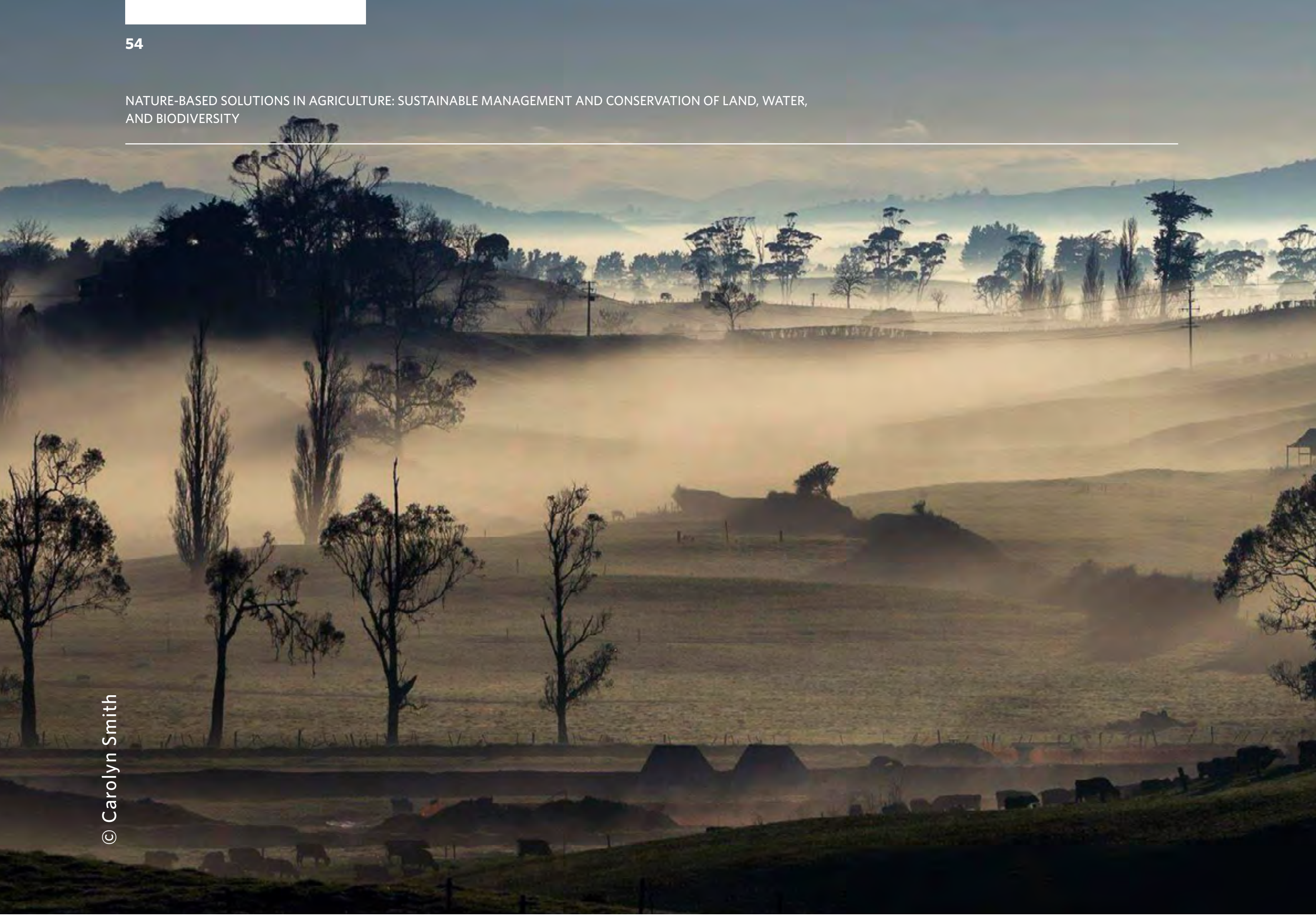
Many of these innovative NbS approaches fall under the umbrella of bioprospecting, i.e., the exploration of biodiversity for new resources of social and commercial value (Barrett and Lybbert, 2000; Beattie *et al.*, 2011). It is carried out by a wide range of established industries in the food production sector such as agriculture as well as a wide range of comparatively new ones such as aquaculture. Much contemporary bioprospecting has multiple goals,including the conservation of biodiversity, the sustainable management of natural resources and economic development. With respect to NbS in agricultural landscapes, the science aspects of bioprospecting continue to evolve in three vital ways.



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First, the discovery of new ecosystem services provided by biodiversity (such as the ones provided in his review). Second, carrying out field studies to confirm and quantify the co-benefits of these NbS. Third, demonstrating the value of millions of mostly microscopic species to local, regional and global economic activities.

With respect to climate mitigation, the quantification of potential contribution of NbS to meeting global goals such as those laid out in the Paris Agreement is conservative in three ways. First, payments for ecosystem services other than carbon sequestration have not been analyzed in the literature reviewed and could spur cost-effective implementation of these solutions beyond the levels identified in this document. As documented here, NbS enhances conservation and adaptation benefits such as biodiversity habitat, water filtration, flood control, air filtration, and soil quality among other services, some of which have high monetary values. Improved human health from dietary shifts toward plant-based foods reduce healthcare expenses and further offset implementation costs (Springmann *et al.*, 2016). Second, these findings are conservative because this review only includes activities and greenhouse gas fluxes where data available in the literature are sufficiently robust for global extrapolation. For example, no-till agriculture (Conservation Agriculture), improved manure management in concentrated animal feed operations (Nutrient Management), adaptive multi paddock grazing (Grazing), and soil carbon emissions that may occur with the conversion of forests to pasture (Avoided Forest Conversion) are excluded from the NbS reviewed here. Future research may reveal a robust empirical basis for including such activities and fluxes within these pathways. Third, the Paris Agreement states goals of limiting warming to "well below 2 °C" and pursuing "efforts to limit the temperature increase to 1.5 °C". Additional investment in all mitigation efforts (i.e., beyond ~100 USD/MgCO_2e), including NbS, would be warranted to keep warming to well below 2 °C, or to 1.5 °C, particularly if a likelier chance of success is desired.

Despite the large potential of NbS, land-based sequestration efforts receive negligible climate mitigation financing. Reasons may include not only uncertainties about the potential and costs but also concerns about the permanence of natural carbon storage and social and political barriers to implementation. A major concern is a potential for Reforestation, Avoided Forest Conversion, and Wetland/Peatland pathways to compete with the need to increase food production. Reforestation and

Avoided Forest Conversion remain the largest mitigation opportunities despite avoiding reforestation of mapped croplands and constraints we placed on avoiding forest conversion driven by subsistence agriculture (Table 2). A large portion of the maximum reforestation mitigation potential depends on the reduced need for pasture accomplished via increased efficiency of beef production and/or dietary shifts to reduce beef consumption. On the other hand, only a ~4% reduction in global grazing lands is needed to achieve <2 °C ambition reforestation mitigation levels, and reduced beef consumption can have large health benefits. A portion of wetland pathways would involve limited displacement of food production; however, the extremely high carbon density of wetlands and the valuable ecosystem services they provide suggest that protecting them offers a net societal benefit.

> Increases in temperature, drought, fire, and pest outbreaks could negatively impact photosynthesis and carbon storage, while **CO_2 fertilization has positive effects.**

Feedbacks from climate change on terrestrial carbon stocks are uncertain in the scientific literature. Increases in temperature, drought, fire, and pest outbreaks could negatively impact photosynthesis and carbon storage, while CO_2 fertilization has positive effects. Unchecked climate change could reverse terrestrial carbon sinks by midcentury and erode the long-term climate benefits of NbS. Thus, climate change puts terrestrial carbon stocks at risk. Cost-effective implementation of NbS, by increasing terrestrial carbon stocks, would slightly increase (by 4%) the stocks at risk by 2050. However, the risk of net emissions from terrestrial carbon stocks is less likely under a <2 °C scenario. As such, overall NbS slightly increases the total risk exposure, yet it will be a large component of any successful effort to mitigate climate change and thus help mitigate this risk. Further, most natural pathways can increase resilience to climate impacts. Rewetting wetlands reduces the risk of peat fires. Reforestation that connects fragmented forests reduces exposure to forest edge disturbances. Fire management increases resilience to catastrophic fire. On the other hand, some of our pathways assume intensification of food and wood yields—and some conventional forms of intensification can reduce resilience to climate change. All of these challenges underscore the urgency of aggressive, simultaneous implementation of mitigation from both Nature-based Solutions and fossil fuel emissions reductions, as well as the importance of implementing NbS and land use intensification in locally appropriate ways with best practices that maximize resilience.

Overall, considerable scientific work remains to refine and reduce the uncertainty of NbS benefit estimates. Recent work (Wood *et al.*, 2015; Oldfield, Bradford and Wood, 2019; DeFries *et al.*, 2015; Bossio *et al.*, 2020; Reguero *et al.*, 2018) has focused on aspects of improved quantification of ecosystem services in agricultural landscapes, particularly in generating evidence of transforming agricultural practices towards multiple co-benefits. Work also remains to refine methods for implementing pathways in socially and culturally responsible ways while enhancing resilience and improving food security for a growing human population. However, delaying implementation of the NbS pathways presented here would likely increase the costs to meet agricultural production, climate, conservation and other societally beneficial goals, while degrading the capacity of natural systems to mitigate climate change and provide other ecosystem services.

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