This chapter is a draft. It will be peer reviewed and subject to change.

6 Mitigation measures in land systems

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Highlights

- Climate mitigation measures in land systems are of high importance to protect existing carbon sinks and the binding of carbon to soil and below- and aboveground biomass in land-based ecosystems. The success of climate mitigation in land systems, relies substantially on water availability and dynamics, which are subjected to unpredictable and unfavourable changes under current and future environmental change.

- Climate change has already substantially altered water cycles in many forest and agricultural systems. The carbon sink strength appears to be deteriorating in some terrestrial ecosystems and has even peaked in some tropical forests.

- Halting deforestation and forest degradation in major forest biomes help preserve favourable water cycle dynamics at the continental-to-planetary and intergenerational scales. Forest biomes are of key importance for the regulation of the Earth’s energy, water, carbon, and nutrient cycle dynamics. Continued deterioration of the regulating effect of forests on the water cycle risks lowering agricultural productivity regionally and globally, as well as turning the forest carbon sinks into carbon sources.

- Mitigation in grasslands and croplands is primarily dependent on improved and water-wise management, and reduction of soil erosion by water through agroecological methods such as agroforestry that can protect and improve carbon stocks below and above ground.

- Mitigation measures in land systems can have notable synergies but also trade-offs with local-to-regional water sustainability goals. Conservation, restoration, and sustainable land and forest management has the potential to decrease flood risks, increase groundwater recharge, and increase water vapour exchange with the atmosphere, thereby enhancing local cooling and regional rainfall. Misguided implementation of mitigation measures can, on the other hand, cause local water shortages, biodiversity loss, and harm to local communities.

6.1. Introduction

Climate mitigation in land systems can mainly be focused around three actions: 1) Reduce emissions from agriculture, forestry and other land use systems. 2) Enhance ecosystems' ability to sequester carbon. 3) Protect existing greenhouse gas (GHG) sinks in ecosystems, such as forests, wetlands, peatlands and soils. IPCC (2022) recently estimated that land systems could provide 20 to 30 percent of the mitigation required to ensure global warming stays below 1.5 C towards 2050.

The mitigation potential of land systems is intimately connected to and dependent on the water cycle. Healthy ecosystems and sustainably managed land systems rely on a stable access to freshwater and predictable weather cycles.

Many of the world's forests, grasslands, and agricultural systems are degraded, suffering from unsustainable management leading to broken water cycles, biodiversity loss and desertification, which also exacerbates climate change. These interactions between the impacts of climate change and level of land degradation can influence soils' carbon storage capacity and ability to act as a carbon sink, thus measures to reduce land degradation also have positive impacts on climate mitigation (Fig. 6.1). Climate change can exacerbate many degradation processes and also introduce new ones (such as thawing of permafrost or biome shifts), which is important to consider in climate mitigation strategies (IPCC 2019). In cultivated agricultural lands, increased decomposition usually leads to reductions in soil organic carbon, which also negatively affects soil productivity and carbon sinks. In forests, young stands with high growth rates can be more efficient at sequestering carbon than older forests, therefore a reduction in biomass carbon stocks is not necessarily an indication of a reduction in carbon sinks. In some cases, for example in areas that are not limited by water, the effects of climate change may lead to increased productivity and carbon stocks, at least in the short term.

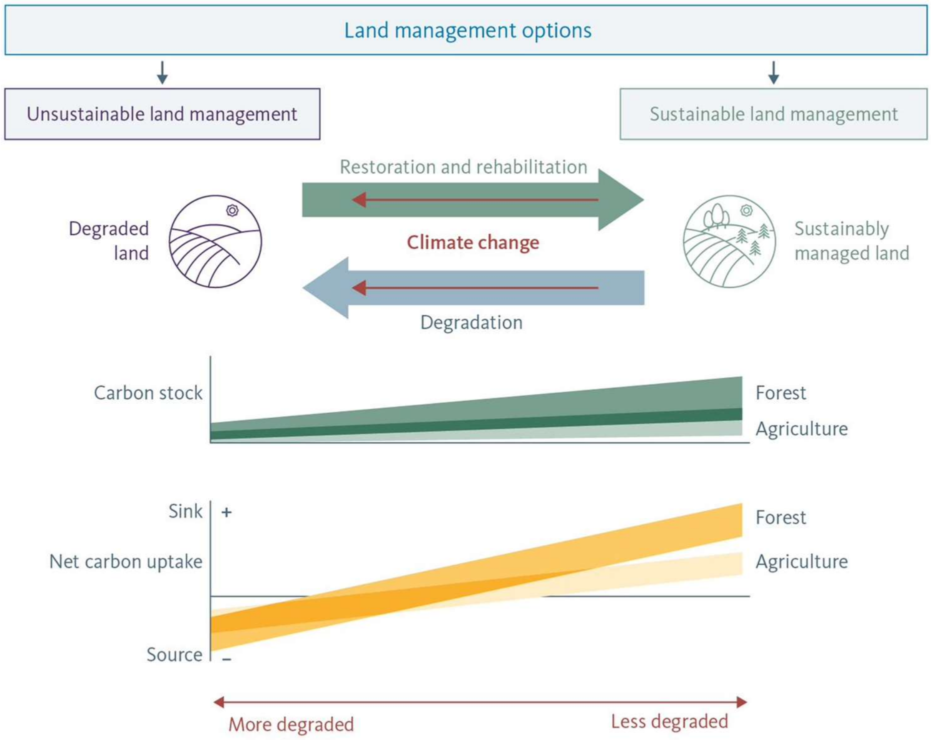

Figure 6.1. Conceptual illustration of how interactions between the impacts of climate change and land-use management can influence soils' carbon storage capacity and ability to act as a carbon sink. (IPCC 2019)

In addition, mitigation in Agriculture, Forestry and Other Land Uses (AFOLU) is the only sector in which large-scale carbon dioxide removal (CDR) may currently and in the short term be possible (e.g. through afforestation/reforestation or soil organic carbon management) (IPCC 2022). Such negative emissions (i.e., net CO_2 removals) from ecosystems are part of all IPCC scenarios that limit global warming to +1.5°C (Masson-Delmotte et al. 2018). Over 90% of AFOLU emissions result from agricultural practices, where IPCC has estimated a mitigation potential of 4.1 $GtCO_{2\text{-eq}}$ yr^{-1} through measures taken across the sector over the next three decades (IPCC 2022). The considerable mitigation potential of land-based mitigation can - and should - be an important component in Nationally Determined Contributions (NDCs) under the Paris Agreement (see Box 6.1).

There is strong evidence that land systems climate mitigation can be effective from a biophysical and ecological perspective. However, to date, the AFOLU sector globally has contributed modestly to net reductions with about 0.65 GtCO2 yr^{-1} of reduction over 2010–2019 or 1.4 percent of the global emissions, mainly due to governance challenges related to lack of institutional support and fragmented and unclear land ownership (IPCC 2022). In addition, mitigation measures may lead to increased competition for water and agricultural land, issues with implementation and permanence, particularly in countries with weak governance (Doelman et al. 2020), other adverse social impacts associated with e.g., land rights, as well as blue water availability. Over 70 percent of freshwater withdrawals are used for irrigation in agriculture and by 2050 an estimated 15 percent increase in water withdrawals is expected (Khokhar 2017). At the same time, about 80 percent of the world's cropland is entirely rainfed, and mitigation measures on these lands are particularly susceptible to impacts of climate change-induced droughts. Globally, over 80 % of all drought impacts are in the agricultural sector. There is a need to plan for and implement integrated approaches that have the potential to synergistically address today's multiple environmental challenges while also improving governance structures (Chapter 9 and IPCC 2019; Pörtner et al. 2021).

Improved cropland management, conservation and restoration of soils, and restoration of degraded land for climate mitigation may lead to several co-benefits, such as reliable access to freshwater, enhanced biodiversity, improved farm production, poverty alleviation, and social development. Implementing these measures may also lead to trade-offs associated with competition for land, for example, concerning social development where nomadic pastoralist cultures' access to grazing lands becomes reduced (Behnke 2018).

In this chapter, we examine the potential and water-related risks of land systems' climate mitigation measures (section 6.2), focusing on forests, croplands and grasslands. In sections 6.3 and 6.4 the extent of land systems' climate mitigation measures' dependence and impact on the water cycle and freshwater resources is mapped. Section 6.5 addresses co-benefits and trade-offs with human well-being and social development goals. Section 6.6 presents the current policy status, and section 6.7 elaborates on the potential implications for governance. The chapter concludes in section 6.8 with a future outlook.

6.2 Mitigation potential in land systems

The selection of mitigation measures addressed in this chapter is based on 1) estimated mitigation potential following the categories of IPCC (2019) (see Table 6.1) and 2) level of impact on or demand for freshwater. Based on those criteria, the chapter focuses on the following measures: reforestation/afforestation and forest restoration, reduced deforestation and forest degradation, improved forest management, improved soil carbon management in croplands, agroforestry, improved soil carbon sequestration in grasslands, and improved rice cultivation. In addition, mitigation measures to shift diets or reduce food losses and waste hold high potential to mitigate climate change. Given the low direct impact on or demand for freshwater of these food-related measures, we address them separately in Box 4.

Land-based ecosystems absorbed around 30 percent of the carbon emissions generated through human activity in the last decade, while land systems also contribute to a quarter of global GHG emissions (IPCC 2022). Thus, land systems have a great mitigation potential - ranging from natural ecosystems to agricultural lands, production forests and other land production systems. Conservation, restoration and sustainable management of land-based ecosystems and production systems are important climate mitigation measures (see Table 6.1, (IPCC 2019)), while many times also supporting local water cycles, biodiversity and local communities. In addition, halting deforestation and forest degradation in major forest biomes helps preserve favourable water cycle dynamics at the continental-to-planetary and intergenerational scales, such as atmospheric moisture regimes and precipitation patterns.

Table 6.1. Climate mitigation measures in land systems with high estimated mitigation potential (IPCC 2019). * Climate mitigation measures that have a minor impact on or demand for freshwater.

Mitigation measure in land systems	**Mitigation potential GtCO2-eq/year 2020-2050**	**Confidence**
Reforestation, afforestation and forest restoration	1.50–10.10	medium
Increase soil organic matter stocks in mineral soils	0.40–8.64	high
Shift to more sustainable diets*	0.70–8.00	high
Improve soil carbon management in croplands	0.25–6.78	high
Reduce deforestation	0.41–5.80	high
Agroforestry	0.11–5.68	medium
Reduce food losses and waste*	0.80–4.50	high
Improve management of soil erosion	0.44–3.67	-
Improve soil carbon sequestration in grazing lands	0.13–2.56	high
Improve livestock management*	0.20–2.40	medium
Improve cropland management	1.40–2.30	medium
Reduce forest degradation	1.00–2.18	high
Improve forest management	0.44–2.10	medium
Improve grazing land management	1.40–1.80	medium
Improve rice cultivation (reduce CH4)	0.08–0.87	-
Improved water management	0.1–0.72	-

6.2.1 Mitigation measures in forests

Forests are well known carbon sinks, and many governments have advanced plans to plant vast numbers of trees to absorb carbon dioxide from the atmosphere in an attempt to slow climate change (Popkin 2019). However, the success of forest mitigation measures relies substantially on the water cycle, reliable precipitation patterns and freshwater availability. Forest mitigation measures, including reducing deforestation and forest degradation; reforestation, afforestation and restoration; and improved forest management are highly dependent on the water cycle, while also impacting it (Figure 6.2). Forests affect many components of the water cycle, including atmospheric moisture transport; infiltration and groundwater recharge; flood moderation; fog/cloud interception; and precipitation recycling at regional and continental scale (Shiel et al. 2019; Ellison et al. 2017; Ilstedt et al. 2016).

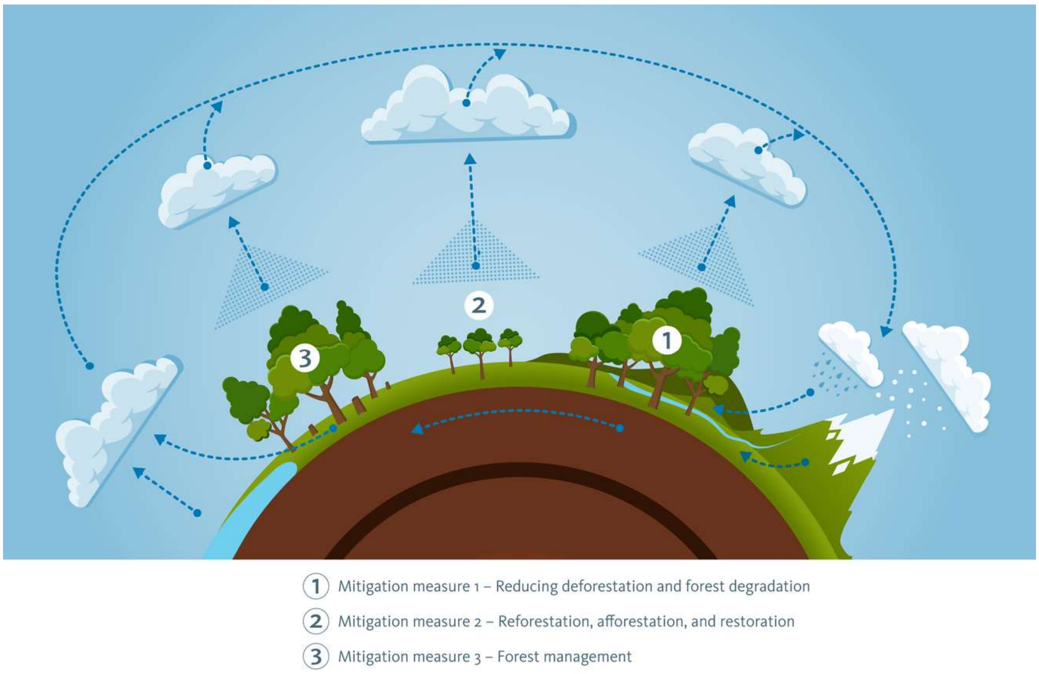

Fig. 6.2. Conceptual overview of forest systems mitigation measures and their impacts on the water cycle. Mitigation measures include 1) Reducing deforestation and forest degradation; 2) Reforestation, afforestation and restoration; 3) Forest management. The water cycle includes atmospheric moisture transport; infiltration and groundwater recharge; flood moderation; fog/cloud interception; and precipitation recycling at regional and continental scales. Figure: Stockholm International Water Institute

Reforestation, afforestation and forest restoration are the mitigation measures estimated to have the highest hypothetical climate mitigation potential globally (up to >10 GtCO2eq yr^{-1} over the years 2020-2050) (IPCC 2019). These measures can considerably impact the water cycle (Hoek van Dijke et al. 2022). Under favourable conditions, increased tree cover can increase precipitation, water yield, and soil infiltration capacity, and reduce both flood and drought risk (Teo et al. 2022). Under unfavourable conditions, increased tree cover can be associated with negative impacts on streamflows, reduced flows to wetlands, and dwindling water tables (Filoso et al. 2017). The higher levels of mitigation potential can only be realised with a high level of water-use (incl. irrigation demand) and with substantial risks for disruptions to the local hydrological balance (such as through streamflow decrease and the lowering of groundwater tables). This is particularly important in cases where water is a limiting factor. Other risks for sustainability trade-offs and conflicts also exist, such as loss of valuable non-forest ecosystems and their associated biodiversity and ecosystem services, and competition for agricultural land.

Reforestation refers to the re-establishment of forest on land that recently has been under forest cover, while afforestation refers to the establishment of forest on non-forested land or land that has been without forests for a long time. These forests can be established either through natural regeneration, plantation or direct seeding; and they can have different purposes, such as timber and pulp production or to ensure the provision of high quality water to an urban area (Zhang et al. 2020). Forest restoration can accelerate the recovery of degraded forest, with special focus on reinstating ecological processes, recovering the forest structure and the biodiversity typical of climax forest (Elliott, Blakesley, and Hardwick 2013). However, the mitigation benefits from restoration are dependent on the initial level of degradation as well as the applied restoration methods (Mackey et al. 2020).

Reforestation, afforestation, and forest restoration can mitigate climate change directly through increased carbon sequestration (Nave et al. 2018), and indirectly through increasing evapotranspiration to reduce local air temperatures (Zhang et al. 2020) and providing moisture recycling (Meier et al. 2021). Carbon is accumulated in plant biomass (i.e., aboveground biomass, below-ground biomass, deadwood, and litter), and as soil organic carbon (Paul et al. 2002; Bárcena et al. 2014). All three of the above mentioned measures should complement, not substitute, measures to reduce deforestation and prevent forest degradation (Kemppinen et al. 2020; Di Sacco et al. 2021), since the carbon stocks, biodiversity, and other ecosystem services provided by old-growth forests can not be provided by newly planted forests within relevant societal and climate change time scales. In addition, preventing deforestation in the tropics is generally highly cost-effective compared to reforestation (7.2–9.6 times as much potential low-cost abatement as reforestation), although tropical reforestation can be more cost-effective in some national cases, particularly in Africa (Busch et al. 2019). Also noteworthy, (assisted) natural regeneration approaches are more cost-effective than planting (Crouzeilles 2020).

The largest forestation potential is in tropical regions considering high economic effectiveness, fast growth rates of trees, and synergies with biodiversity targets (Doelman et al. 2020; Strassburg et al. 2020). Overall, tropical afforestation is found to reduce warming three times more effectively than in the boreal and northern temperate regions (Arora and Montenegro 2011). In contrast to temperate and boreal regions, albedo-induced warming is of less concern in the tropics. At higher latitudes, the effectiveness of afforestation is also hampered by a slower growth rate, and darker tree cover (Zhao and Jackson 2014) than short vegetation types, which can cause substantial surface warming cancelling the carbon sequestration benefits (Schaeffer et al. 2006b; Betts 2000; Arora and Montenegro 2011; Sonntag et al. 2016).

Hotspot areas for forest restoration are primarily found in Brazil, Indonesia, India, Madagascar and Colombia (Brancalion et al. 2019). Hotspots regions for afforestation (as well as reforestation) include South America, China, United States and Sub-Saharan Africa, with South America and Sub-Saharan Africa being responsible for at least 50% of the climate change mitigation potential from afforestation (Doelman et al. 2020). A recent controversial study estimates that globally up to 0.9 billion ha of land are available for canopy cover, representing a total carbon storage potential of up to 205 Gt (range: 133-276 GtC) over decadal timescales (Bastin et al. 2019; Veldman et al. 2019; Lewis et al. 2019; Grainger et al. 2019; Skidmore et al. 2019; Sheil et al. 2019). The realisable potential may however be substantially lower than the overall global potential, if in addition to the water influence on tree cover, also the tree cover influence on water is regarded (Arora and Montenegro 2011; Schaeffer et al. 2006a; Betts 2000; Bala et al. 2007; Veldman et al. 2019; Lewis, Mitchard, et al. 2019; Grainger et al. 2019; Skidmore et al. 2019). Increased droughts and wildfires with severe climate change (RCP8.5) may considerably decrease the potential canopy cover area (by 0.223 billion ha and 46 GtC by 2050), particularly in the tropics (Jean-Francois

Bastin et al. 2019). The realised mitigation effect from forestation measures can further crucially depend on the vegetation type replaced. Tree planting on croplands can increase net carbon storage (Bernal, Murray, and Pearson 2018; Lamb 2018), whereas afforestation on native grassland and peat soils tends to reduce soil carbon stocks, increase wildfire risk, and potentially negate net carbon benefits (Veldman et al. 2017; Wilkinson et al. 2018; Sloan et al. 2018) (see Chapter 5). Further, forestation and tree planting should not be considered as a silver bullet to climate and biodiversity crises without tackling bold steps to reduce GHG emissions (Holl and Brancalion 2020) and without considering the social and environmental justice dimensions, where over 294 million people live on tropical forest restoration opportunity land in the Global South (Erbaugh et al. 2020; Fleischman et al. 2022; Elias et al. 2022).

Reducing deforestation and forest degradation is estimated to have a mitigation potential of 1.41-7.98 $GtCO_{2e}\,yr^{-1}$ over 2020-2050 (IPCC 2019). Globally, the measures also have high potential for climate-water-sustainability win-wins, for instance, in supporting healthy water cycles, safeguarding biodiversity and enhancing the resilience of local communities and urban areas. Primary and old secondary forests are particularly important carbon sinks, as well as regulators of the regional water cycles and climatic patterns (e.g., (Luyssaert et al. 2018; Luyssaert et al. 2008)). Natural forests can be up to 6 times more effective at storing carbon than agroforestry, and up to 40 times more effective than tree plantations (per area unit until 2100) (Lewis et al. 2019)). However, there are concerning signs of increased carbon losses due to drought-induced tree mortality and subsequent carbon sink saturation in tropical forests (Hubau et al. 2020; Green et al. 2019), as well as substantial risks for crossing deforestation tipping points beyond which self-amplifying feedbacks push the biomes towards alternative stable non-forest states (Staal et al. 2020; Zemp et al. 2017).

Stopping forest deforestation and promoting natural regeneration of secondary forests globally is estimated to lead to a negative cumulative carbon emission of about 120 PgC between 2016 and 2100 (Houghton and Nassikas 2018). Natural old-growth forests are able to store carbon for decades, compared to the turnarounds in plantations that is much faster. Natural forests are estimated to have the capacity to sequester 12 Pg C per 100 Mha by 2100, i.e. they are 6 times more efficient than agroforestry (1.9 Pg C) and 40 times better than plantations (0.3 Pg C) at storing carbon (Lewis, Wheeler, et al. 2019).

Tropical forests account for half of the global terrestrial vegetation carbon storage (Lewis, Edwards, and Galbraith 2015)). Existing forests sequester $15.6 \pm 49\ GtCO_{2e}\,yr^{-1}$, while in recent decades under elevated atmospheric CO_2 concentration, deforestation and forest degradation emitted $8.1 \pm 2.5\ GtCO_{2e}\,yr^{-1}$ (Harris et al. 2021). Furthermore, long-term measurements suggest that the tropical rainforest carbon sink strength - i.e., the ability of the forest to absorb more carbon than it releases - has already peaked (since the 1990s in the Amazon and more recently in the African rainforests) primarily due to negative drought and temperature impacts on tree growth and mortality (Hubau et al. 2020). Due to a combination of forest area loss, falling carbon sink strength per forest area unit, and rising anthropogenic carbon emissions, the fraction of anthropogenic CO_2 emissions removed by tropical forests have fallen from 17 % in the 1990s to just 6 % in the 2010s (Hubau et al. 2020). The carbon sink strength will continue to decline, with the magnitude of decline to some extent dependent on the severity of future deforestation and emissions scenarios (Hubau et al. 2020). Nevertheless, Earth system model-based projections, which inform policy and decision making, appear to predict a weak increase in forest carbon sink strength - contrary to the observation-based prediction of future decreases (Koch, Hubau, and Lewis 2021). Thus, to continue to benefit from the tropical forest carbon sinks, it will be critical to prevent forest loss, prevent human-induced fire disturbance, protect the forest water cycle, and enact a rapid halt to anthropogenic greenhouse gas emissions. Highland forests have hitherto received less attention. Nevertheless, recent findings show that the carbon sink strength of Andean rainforests is higher for lowland than highland rainforests (Duque et al. 2021), and montane forest sites in Africa might hold two-thirds more carbon than IPCC has estimated for those areas (Cuni-Sanchez et al. 2021).

In temperate forests, the net CO_2 sink has increased in recent decades due to warming-induced changes in phenology (Keenan et al. 2014) and CO2 fertilisation (Walker et al. 2021). However, this trend appears to have recently slowed down due to a weakening temperature control of spring carbon uptake (Piao et al. 2017), a declining CO2 fertilisation effect on vegetation photosynthesis (Wang et al. 2020), and an increasing water-use efficiency in forests as a response to increasing CO2 concentration (Mathias and Thomas 2021).

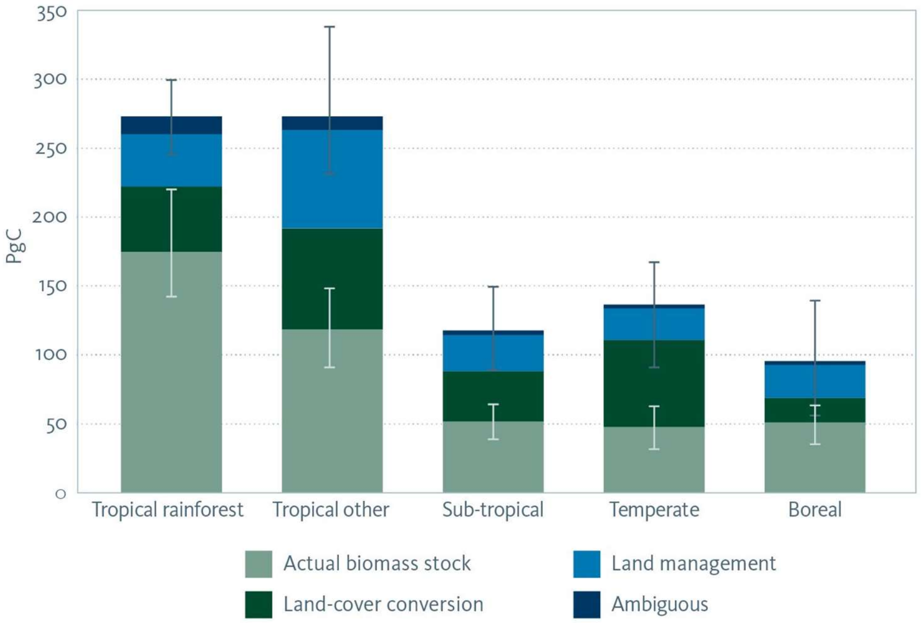

Figure 6.3. Potential for forest conservation and restoration as mitigation measures, considered in terms of a) actual carbon storage in global vegetation (in grams per square metre), b) reduction of carbon storage in global vegetation (in grams per square metre). Source: (Erb et al. 2018)

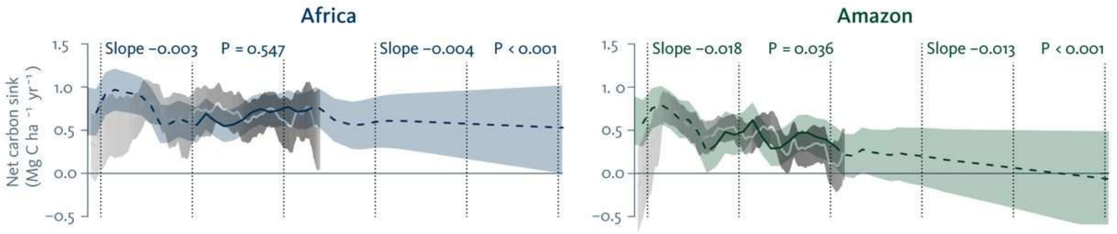

Figure 6.4. The net carbon sink - i.e., the ability of the forest to absorb more carbon than it releases - has already peaked in both the African and the Amazonian forest and is projected to continue to decline (Hubau et al. 2020).

Box 6.1. Sustainable forest management (SFM)

SFM has the potential to mitigate 0.4–2.1 GtCO2-eq yr–1 (IPCC 2019). Climate management measures such as selection of tree species, fertilisation, thinning, irrigation, or prescribed burning (Laclau et al. 2005; Stape et al. 2010; Ontl et al. 2019) can be critical for increasing carbon uptake and ensuring win-wins of both preventive and active forestation mitigation measures. On the other hand, unsustainable forest management risks causing land degradation, reducing carbon stocks of forest land, and increasing greenhouse gas emissions.

Managing forests to preserve and enhance carbon stocks in biomass and soil can have immediate climate benefits but the stored carbon is vulnerable to increased temperatures and drought (Seidl et al. 2017; Jean-Francois Bastin et al. 2019). The effectiveness of forest management mitigation measures is highly site specific and dependent on local knowledge to make informed decisions on e.g., species selection and planting or harvesting strategies. Harvesting natural old-growth forests that have not previously been logged inevitably leads to increased emissions. On deforested land, on the contrary, reforestation interventions leading to sustainable forestry can increase both carbon storage and biodiversity.

The time perspective of forest management initiatives is of great importance for the balance between enhancing carbon storage and meeting the demand for wood products and bioenergy. Forest carbon sinks are affected by the length of rotation time and logging intensity (Mackey et al. 2020; Lundmark et al. 2018), where longer rotation times, continuous forest cover and reduced harvesting have positive effects on the amount of stored carbon (Bartlett et al. 2020). Wood products are often presented as substitution solutions to reduce the dependency on products with high negative impact on climate change, such as materials and energy from wood products replacing fossil-intensive materials and energy. The trade-off between maximising forest carbon stocks and maximising substitution is dependent on many factors, including the state of the managed forest, regrowth rates and estimated emissions from the product or energy source that is substituted (REF). In a long-term time-perspective, sustainable forestry can be part of increasing carbon uptake and slowing down global warming, while also providing timber, fibres and bioenergy (Högberg et al. 2021).

SFM is a globally recognized concept that can have multiple objectives, including water quantity, quality and flows; timber production; biodiversity and carbon sequestration and storage. Within SFM, efforts are focused on society's various needs, including water security. SFM can be defined as ‘the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems’ (Mackey et al. 2020). Sustainable forest management that enhances forest growth and reduces wildfire risk can lead to increased carbon sequestration and storage in forest soils (Mayer et al. 2020). In recent decades, soil C stocks in boreal and temperate forest areas have increased slightly (ca 6 percent) following forest area expansion due to reforestation of agricultural land and reduced harvesting in young secondary forests, while soil C stocks in tropical forests have declined slightly (ca 7.5 percent) due to deforestation (Scharlemann et al. 2014). However, the mitigation potential achieved through protecting and enhancing forest soil carbon stocks is quite small (9 percent) compared to e.g., soil carbon stored in grasslands and agriculture (47 percent) (Bossio et al. 2020).

6.2.2. Mitigation measures in croplands and grasslands

Humans have been growing crops and herding livestock for almost 10,000 years and estimates show that altogether the derived land use changes have reduced global soil carbon by 116 Gt (Sanderman, Hengl, and Fiske 2017). Anthropogenic land-use has major impacts on the carbon source/sink function of ecosystems, and degraded lands cause increasing GHG emissions, which may have feedback effects on the global climate system. In addition, combinations of global change drivers such as elevated atmospheric CO2 concentration, warming, fertilization, grazing, and land-use change influence croplands and grasslands carbon sequestration. The water cycle is of high importance for carbon sequestration and storage in soils, while both land use and climate change may threaten the effect of this function.

The mitigation potential in agricultural systems is estimated to 4.1 (1.7–6.7) GtCO2-eq yr-1 (IPCC 2022). Important mitigation measures include improved cropland and grassland soil carbon management, agroforestry, and improved rice cultivation. These systems are highly dependent on reliable access to freshwater and an intact water cycle. In fact, agriculture accounts for 70% of freshwater use worldwide, mainly for irrigation (FAO 2014). Unsustainable land-use has profound effects on the fluxes and availability of freshwater, both locally in terms of green and blue water quantity and quality and regionally in terms of changes in evapotranspiration and precipitation. For instance, groundwater pumping for irrigation often risks depleting streamflow, depleting watershed functioning, etc, leading to drought and reduced access to freshwater for downstream communities. In addition, agriculture is a major source of water pollution, especially from agricultural fertiliser and pesticide runoff and discharge from livestock production (see Chapter 5).

Improved management of soils in croplands and grasslands can have a positive effect on the vegetation cover which may influence soil moisture in several ways; it can reduce the water evaporation by shading the soil and regulating soil temperature, it can decrease the magnitude of water erosion by reducing the impacts of rainfall, runoff and flood events on the soil, and it can reduce streamflow and sediment export by intercepting runoff and promoting water infiltration.

Improved soil carbon management in croplands

Measures to keep a continuous vegetation cover and thus increase the soil carbon stock requires sufficient amounts of water. In agriculture, sustainable land management practices, such as reduced tillage intensity and the use of perennial crops, have the potential to both enhance water use efficiency and preserve soil carbon stocks while also reducing input costs (Beare, Hendrix, and Coleman 1994; Yuan Li et al. 2019).
Soil and water conservation practices aimed at reducing water erosion and surface runoff, controlling floods and improving soil infiltrability, are crucial components to successfully restore degraded soils. Sustainable

soil and land management practices, including restoration and conservation agriculture, can improve soil infiltrability resulting in reduced surface runoff and erosion (Bargués-Tobella et al. 2020).

Soil erosion by water is causing major reductions in the global soil carbon stock, leading to reduced soil productivity and land degradation. Measures to reduce soil erosion are key for protecting soil organic carbon stocks, and thus serve as important tools for mitigating climate change (Amundson and Biardeau 2018). A recent study is predicting that conservation agriculture can reduce global potential soil erosion rates by ~5% between 2015 and 2070 (Figure 6.5) (Borrelli et al. 2020). Further, the study indicates a global trend where a more intense hydrological cycle due to increased temperatures may increase soil erosion.

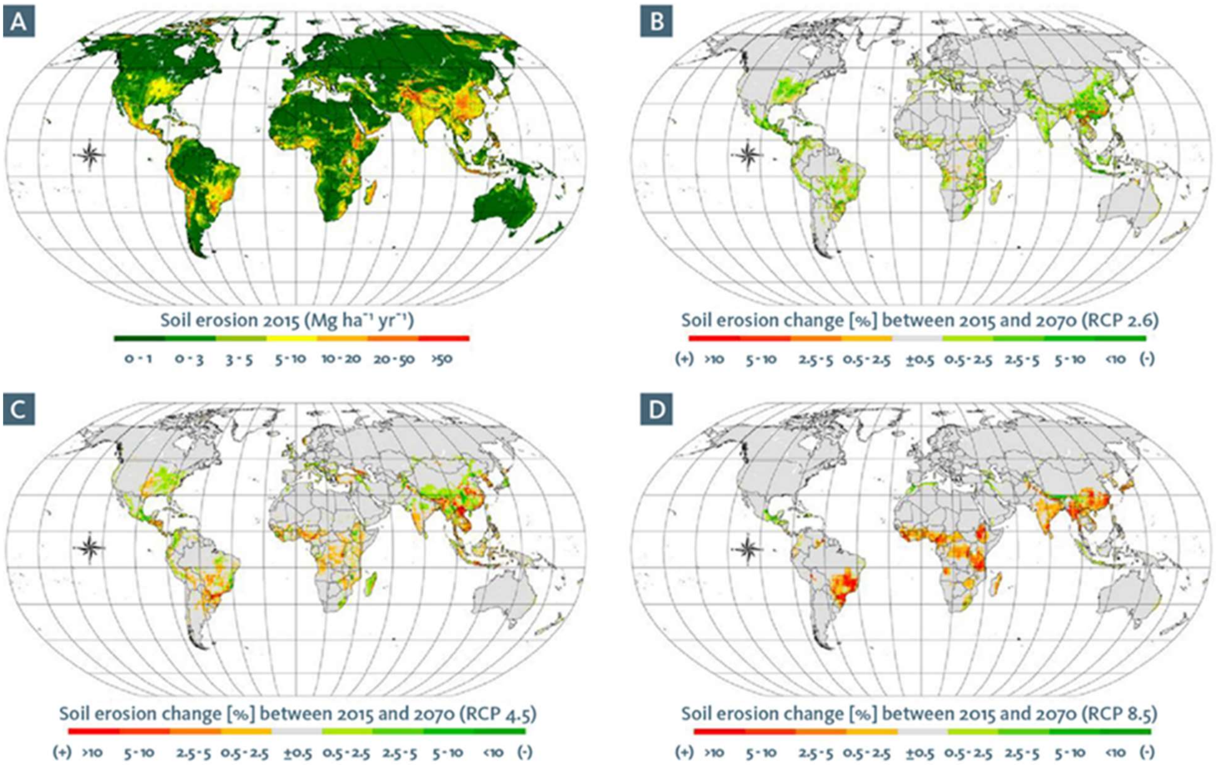

Fig 6.5. Predictions of annual average erosion rates between 2015 and 2070 by modelling change in potential global soil erosion by water using three alternative scenarios (2.6, 4.5, and 8.5) called Shared Socioeconomic Pathway and Representative Concentration Pathway (SSP-RCP). The scenarios suggest different impacts on soils water erosion by 2070. A) Soil erosion in 2015 B) A 10 percent soil erosion decrease by 2070 (2.6) C) A 2 percent soil erosion increase by 2070 (4.5) D) A 10 percent soil erosion increase by 2070 (8.5). (Borrelli et al. 2020).

Agroforestry

Trees in agricultural land have a positive influence on the soils' ability to absorb, store and release water through enhanced litter inputs and the activity of roots and soil fauna (Benegas et al. 2015; Bargués-Tobella et al. 2020). The integration of trees on agricultural land can enhance the mitigation potential of a farm by increasing soil carbon sequestration and reducing GHG emissions. The adoption of agroforestry practices can therefore have strong mitigation potential, while also providing multiple social and ecological co-benefits (IPCC 2019), such as biodiversity, enhanced crop production and reduced food and nutritional insecurity.

Agroforestry can transform degraded or less-productive lands and support the hydrological cycle, for instance, by regulating the supply of water, improving soil health and reducing erosion. Restoring degraded landscapes is becoming increasingly important to mitigate climate change, and sustainable agroforestry practices have a central role to play in this development. Agroforestry offers solutions that can contribute to climate change mitigation while also contributing to climate change adaptation and increased water security. Thus, agroforestry is increasingly being addressed in international policy as a sustainable land management practice to restore degraded lands and reduce erosion (IPCC 2019). As an example, forest and landscape restoration (FLR) is a long-term restoration process that has gained extensive attention internationally in recent years. Most FLR opportunities are in the form of mosaic restoration, where agroforestry plays a critical role (Minnemeyer et al. 2011). The main focus of FLR is twofold; to regain ecological functionality while also enhancing human well-being across deforested or degraded forest landscapes. Compared to other restoration practices included in FLR, agroforestry is particularly effective in restoring biodiversity and ecosystems while also delivering food and income (FAO 2022).

Improved soil carbon sequestration in grasslands

Grassland soils store high quantities of carbon and other key nutrients and, hence, play a major role as carbon sinks in the global biogeochemical cycle. In grasslands most of the biomass is below ground, aggregated into roots (~700-1000g m-2 with root lengths up to >2m) where most of the carbon is stored. Consequently, grassland soils hold relatively large quantities of organic C and store around 28%–37% of the global soil organic C pool (Yadvinder 2002, Lal 2004). Despite their low aboveground biomass, grasslands are thus important net sinks for the atmospheric C, collecting nearly 0.5 PgC per year (Scurlock & Hall 1998, Imer et al 2013). Due to seasonal dieback the fine roots are easily but often only partly decomposed by soil organisms and the containing C and carbon containing fibres deposited into soil. Moreover, the extended strongly branched root system stabilises soil surfaces resulting in significantly decreased soil weathering rates and soil degradation in usually highly exposed grassland plains. With slow decomposition of organic material, and accumulations of organic matter over long-term resulting in highly fertile and carbon rich soils.

Grasslands, including savannas with scattered trees and open-canopy grassy woodlands, cover approximately 40% of the global land surface (Dixon et al. 2014). Restoration of grasslands has received far less attention than that of forests and the understanding of the kind of activities that should be included in large-scale restoration of grasslands is limited (Buisson et al., 2019). In grasslands with scattered trees, soil infiltration capacity increases in the vicinity of trees. In systems with an open tree cover, such as agroforestry parklands or open woodlands, it is important to consider the water balance both in areas under trees, and in small and large gaps among trees (Bargués Tobella et al. 2014). Better soil structure under trees improves infiltration capacity, thereby reducing surface runoff and eventually improving groundwater recharge.

The Great Green Wall initiative is an example of a large-scale restoration initiative for grasslands and savannas in the Sahel and Sahara region that often experience severe droughts and where soil and land degradation is common. The initiative, therefore, includes activities on water and soil conservation measures to increase climate change resilience – in fact, the most common Sustainable Land Management activities reported in the 2020 Great Green Wall status report (UNCCD, 2020) were forest and watershed management. Box 6.2 below summarises experiences and practices introduced in the GGW that can generate climate change benefits through carbon sequestration in soils and vegetation, while also improving the hydrology and resilience of landscapes.

Box 6.2. The Sahara and Sahel Great Green Wall

Reducing and reversing land degradation is important for achieving the Sustainable Development Goals (SDGs) in the Sahelian region and the targets related to food and water security (SDGs 2 and 6), and life on land (SDG 15), to balance losses and gains of productive land to achieve land degradation neutrality (Cowie et al., 2018). The Great Green Wall for the Sahara and the Sahel Initiative (GGWI) is a Pan-African programme launched in 2007 by the African Union (AU). Starting with an original 11 core countries from Senegal to Djibouti (Figure 1), the GGWI has now expanded to more countries including the drylands of North and South Africa and represent a total restoration potential of over 600 million Ha (UNCCD, 2020). Its goal is to reverse land degradation and desertification in the Sahel and Sahara, enhance food security and support local communities to adapt to climate change. Initially proposed by former Nigerian President Olusegun Obasanjo and then by Senegalese President Abdoulaye Wade, the African Union endorsed a joint Plan of Action in 2007. Since then, the European Union (EU), the Global Environment Facility (GEF) and the World Bank (WB), among others, have provided financing for a number of projects to implement the GGWI. Some of the notable projects include the Sahel and West Africa Program in Support of the Great Green Wall Initiative (SAWAP), and the Building Resilience through Innovation, Communication, and Knowledge Services project (BRICKS) (UNCCD, 2020; Goffner et al., 2019).

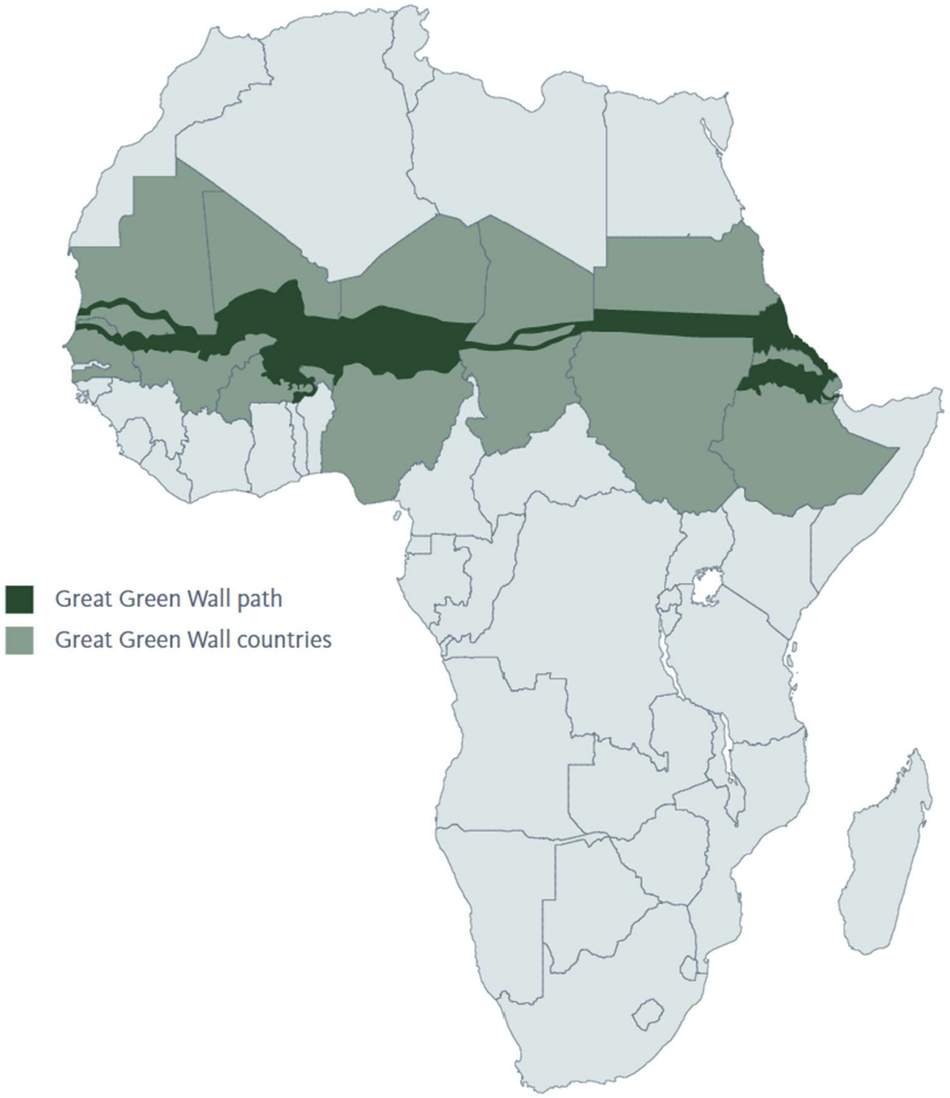

Figure 6.6. The Great Green Wall path in the original 11 member countries (UNCCD, 2020)

The GGWI has moved beyond its original conception as a wall of trees into a mosaic of Sustainable Land Management (SLM) practices to create resilient landscapes. The objective is to restore 100 million ha of land, sequester 250 million tons of carbon and create 10 million jobs by 2030 (UNCCD, 2020). Communities and their preferences are at the heart of forest and landscape restoration activities and the focus is not only on trees, but also on feed, medicines, food, and fuel. Site characteristics such as rainfall regimes, land cover, soil types and topography determine which SLM measures are most appropriate for each location. For example, the most common practices in Burkina Faso, Mali and Niger are Soil and Water Conservation (SWC) measures, sand dune stabilisation and soil fertility improvement, while in

Mauritania, water harvesting and sand dune stabilisation techniques are the most important SLM measures (Chirwa and Larwanou, 2017).

Moreover, water is at the centre of restoration in drylands as interventions aiming at increasing vegetation cover and carbon sequestration improve soil water availability, while direct water related activities benefit vegetation greening. The role of tree cover in the hydrological cycle and its effect on groundwater and stream flow yields in the Sahel has been debated extensively (e.g. Ellison and Speranza, 2020). Catchment studies looking at the impacts of tree cover on water yields show that forestation leads to reductions in streamflow due to the higher evapotranspiration (ET) from trees, while the opposite happens with deforestation (e.g. (Farley et al. 2005; Bosch and Hewlett 1982)). In landscapes with scattered trees, such as the Sahel, soil infiltration capacity increases in the vicinity of trees as far as 20 m away from the closest tree stem. In an agroforestry parkland in Burkina Faso, groundwater recharge was maximised with an intermediate tree cover (Ilstedt et al. 2016). In Senegal, planting and preserving shrubs within farmlands increased millet and groundnut yields as well as soil carbon while contributing to higher water use efficiency through increased soil porosity particularly on sandy soils (Bright et al., 2021). Sites treated with Zaï and half-moons (demi lune) in Niger exhibited high soil-water storage, promoting higher vegetation productivity and millet yields compared to control sites particularly in drier years (Wildemeersch et al. 2015). For their part, SWC practices in Burkina Faso such as stone bunds, gullies and permeable dams have contributed to the regeneration of trees and shrubs which further sequester carbon (Reij et al. 2009).

Overall, actions that can generate climate change benefits through carbon sequestration in soils and vegetation, while also improving the hydrology and resilience of landscapes include (Berrahmouni and Sacande, 2014; Sacande and Berrahmouni, 2016):

- Promoting natural regeneration, in which farmers protect and manage the natural regeneration of native species in forests, croplands and grasslands.
- Investing in large-scale land preparation and enrichment planting where degradation is so severe that natural vegetation will not regenerate on its own; communities select the native woody and grass species to be used.
- Fighting sand encroachment by establishing and protecting native woody and grassy vegetation adapted to sandy and arid environments.
- Mobilising high-quality seeds and planting materials of well-adapted native species to build ecological and social resilience.
- Developing comprehensive value chains that benefit local communities and countries and enable the flourishing of green economies and enterprises.

The most common SLM techniques (Table 6.2) adopted in the context of the GGW are forest and watershed management, terracing and soil measures, assisted natural regeneration and reforestation. Other common activities that often cover smaller areas are multipurpose gardens, nurseries and fire and wind breaks (UNCCD, 2020). Through the adoption of these measures, the GGW has so far directly contributed to the restoration of 4MHa of degraded lands and set the momentum for other national and international projects that have led to the restoration of an additional 17.8 MHa in the core countries totaling an estimated carbon sequestration potential of 138 MtC (UNCCD, 2020). The various value chains created through GGW interventions including honey, Arabic gum, baobab and fodder have also contributed to the creation of 335,000 jobs (UNCCD, 2020).

Table 6.2. Some of the most common SLM practices in the Sahel and their benefits (Maisharou et al., 2015; Chirwa and Larwanou, 2017)

	Production	**Land rehabilitation**	**Plant protection**	**Erosion control**	**Water harvest & retention**
Forest management & Agroforesty	FMNR Multi-purpose gardens Plant seedlings	FMNR Reforestation			FMNR Reforestation
Pasture and crop management	Intercropping Fire breaks Enclosures	Mulching Intercropping Fallow Direct seeding Contour ploughing Enclosures	Intercropping Cover crop Fallow Fire breaks Wind breaks	Cover crops Contour ploughing Wind breaks	Intercropping Contour ploughing Mulching Cover crops Wind breaks
Soil fertility management	Dune fixing Composting Terrace cultivation	Zero tillage Composting		Dune fixing Terrace cultivation	Terrace cultivation Zero tillage
Water management	Half-moon Zaï	Half-moon Zaï Rock dams Trenches		Rock dams Trenches Stone bunds	Half-moon Zaï Rock dams Contour bunds

However, progress has not been homogenous amongst the countries with some showing more achievements than others (UNCCD, 2020). Mirzabaev et al. (2021) evaluated the economic costs and benefits of land restoration under the GGWI programme. The results show that the average annual costs of land degradation due to land use and land cover changes in the entire Sahel region during 2001–2018 period were equal to USD 3 billion. About 10 years are needed for all land restoration activities to reach positive benefit-cost ratios from the social perspective. The amount of investments needed for land restoration across the Sahel is estimated to be between USD18–70 billion (Mirzabaev et al. 2021). In order to speed up the pace and scale up interventions, a renewed financial commitment took place at the

One Planet Summit in January 2021 leading to a pledge of over USD19 billion by several multilateral and bilateral organisations as well as the creation of the GGW accelerator to facilitate the coordination of donors and stakeholders involved in the GGW (https://www.greatgreenwall.org/).

Amongst the many programs in place to support the GGW, the GEF is funding projects to further enhance collaboration between the various countries and stakeholders in the GGW to create an enabling environment for scaling up of SLM interventions and policies as well as to support the mobilisation of funds for implementation of SLM in the GGW, and to integrate and harmonise different scientific tools and methods used to monitor interventions and their environmental and livelihood impacts in support of future investments. The project "Large-scale Assessment of Land Degradation to guide future investment in SLM in the GGW countries" takes stock of previous SLM related GEF projects in the four pilot countries of Senegal, Niger, Burkina Faso and Ethiopia (Figure 2). The ongoing analysis of these projects will serve as a basis for an indicator framework for the monitoring of socio-economic impacts (O'byrne et al. 2022), a scaling evaluation framework to inform future SLM investments in the region (Mechiche-Alami et al. 2022), as well as the identification of land degradation hotspots and an impact assessment of interventions. The ultimate goal is to maximise environmental and socio-economic benefits of SLM investments, such as carbon sequestration and regulation of water, contributing to food and water security in the Sahel. Through a combination of partners [1], ranging from remote sensing companies, international organisations and research institutes, this project develops science-based assessments and provides training to technical staff of the GGW country offices.

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[1] UNEP, Agrhymet, OSS, LUCSUS, NASA, ESA, Sistema, DHI.

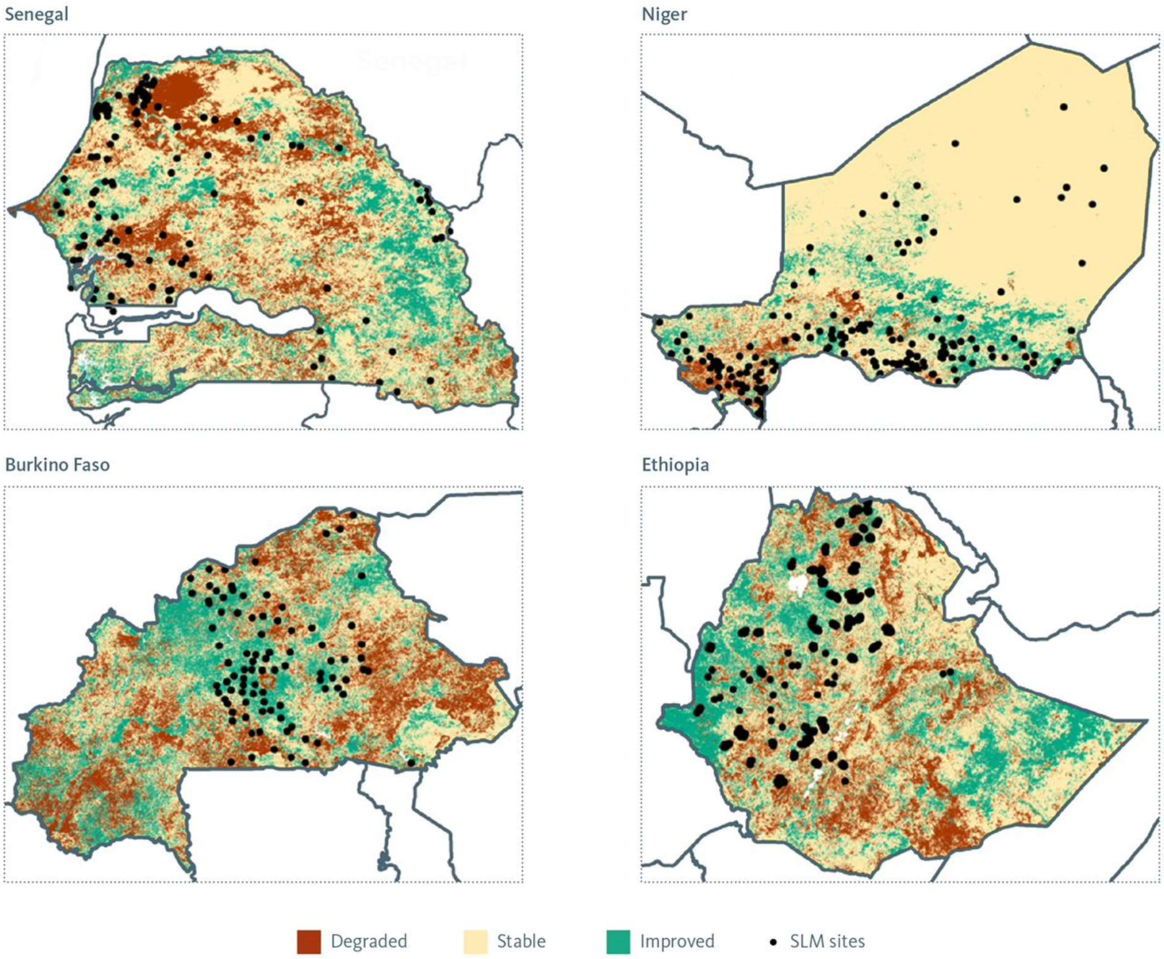

Figure 6.7. SLM intervention sites under GEF projects and assessment of land degradation (based on trends.earth) between 2001 and 2018 in Senegal, Niger, Burkina Faso and Ethiopia.

Improved rice cultivation

Rice is a staple food for more than 50 percent of the world's population, and rice paddies - to their extent the largest artificial wetland type globally - constitute an important source of GHG emissions (IPCC 2022). The global mitigation potential from improved rice cultivation has been estimated to a range between 0.08-0.87 GtCO2-eq yr-1 between 2020 and 2050 (IPCC 2019). Rice cultivation emissions are to 90 percent associated with methane emissions from anaerobic conditions. The main mitigation potential lies in improved management measures, i.e. considering which flooding regime to use (see Box 6.3). Continuous flooding results in much larger methane emissions than irrigating frequently during the growing season, e.g. alternate wetting and drying (Adhya et al., 2014). Other factors contributing to GHG emissions stem from fertiliser application and water pumping.

About 90 percent of rice is produced and consumed in Asia, but other cultivation regions are on the rise, such as sub-Saharan Africa (IPCC 2019) (Carlson et al. 2016). The demand for rice is growing continuously, and global rice production is projected to increase by 13 percent by 2028 compared to 2019 levels, with the largest increase in Africa and Asia (OECD/FAO 2019). Globally, the area under rice cultivation has grown by 11% between 1990 and 2019 (FAO 2021c) and now occupies more than 160 million hectares, of which Asia covers about 88 percent (Chakraborty et al. 2017). Although the highest area under rice in the world (43.8 m ha) is in India, the average productivity is higher in the USA, China, and Japan. A slight decline in emissions from rice cultivation is estimated by 2030, due to expected dietary shifts from rice to protein as a result of increasing per capita income in certain regions (USEPA 2019).

Box 6.3. Improved rice cultivation in India

In India, where 85 percent of the population have rice as their staple food, there has been an increasing trend in rice area and production from 30.8 to 43.8 million ha from 1950 to 2021, with an increase in production from 20.6 to 122.3 million tonnes (Agriculture situation in India, 2021). The productivity increased from 668 to 2400 kg ha-1 during the corresponding period (Dey, 2020). The eastern part of the country, including the states West Bengal, Bihar, Odisha, Eastern Uttar Pradesh, Assam, and Eastern Madhya Pradesh, is an important area for rice cultivation, accounting for about 63.3 percent of India's total area under rice cultivation.

India is a net exporter of rice. About 80 percent of the rice procured in the country is for domestic consumption and about 20 percent, i.e. approximately 18 million tonnes, is exported (Cotecna, 2021). Saudi Arabia, Iran, Iraq, Yemen and UAE are major importing countries of basmati rice, whereas Benin, Nepal, Togo, Senegal and Cote d'Ivoire are major importing countries of non-basmati rice from India. India has exported 13.09 million metric tonnes of non-basmati rice valued at about USD 4800 million, whereas basmati rice exports are 4.631 million tonnes valued at USD 4018 million during the year 2020-21 (APEDA, 2021).

Rice production systems and the extent of methane emissions

In India, rice production systems are classified based on soil water conditions and categorised into the following four broad groups (Rao et al., 2017, Meera et al. 2014). The extent of methane emissions from these production systems is presented in Table 1 below.

1. **Irrigated rice ecosystem** is grown in bunded fields with assured irrigation for one or more crop rotations per year. Usually, farmers try to maintain 5–10 cm of water on the field. The wet season (June to October) is the main season for rice cultivation (Rao et al. 2008). In India, about 22 million hectares area is under irrigated rice ecosystems, which is about 49.5% of the total rice area in the country.
2. **Rainfed upland rice ecosystem.** About six million hectares of area is under upland rainfed rice cultivation, which accounts for 13.5 % of the total area under rice crop in the country. Monsoon season (June-September) is the main season for rice cultivation in this ecosystem. In this ecosystem, mostly direct sown rice is grown and in the dry season the rice fields are generally dry and unbunded.
3. **Rainfed lowland rice ecosystem** is grown in bunded fields that are flooded with rainwater for at least part of the cropping season to water depths that exceed 100 cm for no more than 10 days.

In India, this area accounts for 32.4 % of the total area under rice cultivation. There is much variation in water depth in this ecosystem, which can be shallow (up to 25 cm), medium deep (up to 50 cm), or deep (up to 2 m). Depending on the water depth in the field, medium- to long-duration cultivars are grown. The ecosystem faces shortage of water during the establishment period of the crop and excess water during the later stages. For better performance, the cultivars grown in this ecosystem should have tolerance to drought in initial stages and submergence at later stages, and elongation ability in semi-deep- or deep-water situations, due to little control on water.

4. **Flood-prone rice ecosystems** are prevalent in those areas where farmers have to face temporary submergence of 1–10 days or long period submergence of 1–5 months in depths from 50 to 400 cm or more. This is also adopted where daily tidal fluctuations also cause complete submergence (Mohanty et al. 2013). In India, about 4.6 % of the total rice-grown area is under a flood-prone rice ecosystem. Yields in these ecosystems are very low (1.5 t ha^{-1}) and variable. June to November is the main season for flood occurrence during the wet season. Rice varieties are selected according to their level of tolerance to submergence.

Table 6.3. Methane emissions from different rice production systems, assessed for the year 2007. Source: Bhatia et al., 2013

Ecosystem	**Water regime**	**Rice area (m ha)**	**Methane emission (Million Tonnes)**
Irrigated	Continuous flooding	6.7	1.14
	Single aeration	8.2	0.55
	Multiple aeration	9.9	0.15
Rainfed	Flood prone	3.7	0.70
	Drought prone	9.0	0.70
Deep water		1.4	0.26
Upland		4.9	0.15
Total		**43.8**	**3.65**

Technological options of rice cultivation to minimize water use and emissions

Based on the method of rice establishment, the rice production systems are categorized into (a) transplanted rice production systems and (b) direct-seeded rice production systems. Direct-seeded rice production systems have been further categorized as (i) dry-seeded rice (dry-DSR) system, (ii) wet-seeded rice (wet-DSR) system, and (iii) water-seeded rice (water-DSR) system (Rao et al., 2017)

Direct seeded rice (DSR) can significantly reduce the greenhouse gas emissions and contributes to water saving since the water required for nursery preparation and puddling is saved. Direct seeded rice is a feasible alternative to conventional puddled transplanted rice with the potential to save water, energy, and labour and reduce greenhouse gas (GHG) emissions (Pathak *et al,* 2011). DSR (dry) can save water up to 8-17% of the irrigation water compared to traditional puddling methods (Gupta et al., 2016). Higher yields are also reported with the adoption of DSR to the extent of 10-18% with less irrigation water. DSR was recommended for the northwestern states of Punjab and Haryana, the rice bowl of India where significant area is under rice grown with the groundwater (Shah *et al.,* 2018). Continuous flooding, nitrogen fertilizers and machinery are responsible for the higher GHG emissions from conventional methods of planting. Puddling and continuous submergence of rice fields facilitates the activity of methanogenesis by methanogenic bacteria, thereby increasing methane emissions (Pathak et al., 2013). In contrast, the aerobic conditions of DSR reduce the methane emission and the global warming potential (GWP) to the extent of 40-70% (Basavalingaiah *et al.,* 2020).

Aerobic rice is another important water saving technology which contributes to water saving up to 28% and extent of methane gas mitigation ranged between 21-93%. The aerobic rice cultivation limits the water to the saturated field conditions and avoids submergence which minimizes the methane emissions. System of rice intensification (SRI) and modified system of rice intensification also minimizes the greenhouse gas emissions where the soil is kept moist but not inundated thus reducing the methane emissions significantly up to 38%. These practices also contributed to water saving up to 27-36% with yield improvement up to 9-22% (Table 2). Due to maintenance of aerobic conditions in SRI, the activity of methane producing bacteria was less and thus methane production was much lower under SRI. As the system of cultivation aims at saturation of the field, it encourages the growth and activities of the oxidizing bacteria and decreased activity of the reducing bacteria, leading to a gradual increase in the redox potential of soil (Rajkishore *et al.* 2013).

Table 6.4. Contribution of improved systems of rice cultivation to water savings, yield improvement and mitigation of GHGs

Systems of rice cultivation	**Water savings (%)**	**Yield improvement (%)**	**Reduction in methane emissions (%)**	**Reference**
Direct seeding of rice-Dry	8-17	10-18	16-95	Singh *et al.,* (2009); Pathak et al., (2013); Bhatia *et al.,* (2013); Gupta *et al.,* (2016); Majumdar, (2003); Chakraborty *et al.,* (2017); Kaur and Singh, (2017)
Direct drill seeding of rice	30	-9	42	Pathak *et al.,* (2011)
Direct seeding of rice	10-30	7-16	Reduction in global warming potential by 40-70	Kakraliya *et al.* (2018); Adhya *et al.,* (2014); Basavalingaiah *et al.,* (2020)
Aerobic rice	26-28	-	21-93	Pathak *et al.* (2012); Sharma *et al.,* (2016)
System of rice intensification	27	9-15	29-38	Suryavanshi *et al.,* (2013); Rajkishore *et al.* (2013)
MSRI (Modified system of rice intensification)	36	22	30	Jain *et al.,* (2014)

Contribution of water management practices to reduced emissions

Improved water management practices in rice cultivation create aerobic conditions which control soil microorganism's activity resulting in reduction of methane emissions. Changes in soil moisture by various irrigation methods such as alternate wetting and drying (AWD), mid-season drainage and intermittent irrigation, intermittent flooding and intermittent drainage which affects the soil redox potential, regulate release of GHGs. AWD results in a substantial reduction of methane production because the time intervals between dry and wet conditions assist the shift from aerobic to anaerobic soil conditions and contribute towards 20-60% methane reduction and 45-90% global warming potential. Water saving of 23-83% at various locations of India has been observed under AWD (Oo *et al.,* 2018). Under AWD, rice fields are subjected to alternate cycles of saturated and unsaturated conditions where irrigation is interrupted and water is allowed to subside until the ponded water disappears and the soil reaches a certain moisture level (Adhya *et al.,* 2014). Similarly, in intermittent flooding and drainage methods, the field is alternately watered and drained, has a large potential to reduce methane production from soil as this irrigation method facilitates soil oxidative conditions by enhancing root activity, soil bearing capacity and minimizes water inputs that create anaerobic conditions. This increases the diffusion of oxygen into the paddy soils and reduces methane emission to the extent of 15-88% (Mohanty *et al.,* 2017). Pathak (2012) reported a reduction in GWP by 33% using mid-season drainage in rice over continuous flooding (Table 6.5). Intermittent drainage in rice, creating alternately anaerobic and aerobic conditions, is considered to be one of the best options for reducing methane emission (Tyagi *et al.,* 2010). Besides mitigating methane emission, drainage practices can also conserve water and improve rice yields.

Despite AWD's benefits and its potential, the adoption of AWD has been limited, perhaps largely due to farmers' apprehensions that this may lead to yield reduction (Carrijo *et al.*, 2017). Thus, alternatives such as mild AWD are recommended where the cycle of unsaturated conditions is limited compared to AWD (Carrijo *et al.*, 2017). A meta-analysis of 56 studies showed that under mild AWD, rice yields were not reduced in most cases (Carrijo *et al.*, 2017) since the roots of the rice plants will still be able to take up water from the saturated soil and the perched water in the root zone. Deelstra *et al.* (2018) reported an increase in water productivity of 0.59 kg/m^3 under AWD over conventional paddy rice (0.22 kg/m^3) because of water saving and better yields in two districts of Telangana in the Krishna River basin. Irrigation scheduling helps to optimize the application of the right amount of water at the right time and place to optimize crop production, conserve water, and improve performance of irrigation systems. Scheduling irrigation with low cost tensiometers is one alternate approach to optimize irrigation water in rice and wheat, which reduced the number of irrigations in rice, resulting in about 13% water savings (Vatta *et al.,* 2018).

Table 6.5. Irrigation management practices and the extent of water savings and mitigation

Systems of rice cultivation	**Reference**	**Water savings (%)**	**Reduction in methane emissions (%)**
Alternate wetting and drying	Adhya *et al.,* (2014)	23-43	GWP by 45-90
Alternate wetting and drying	Oo *et al.,* (2020); Oo et al., (2018); Khosa *et al.,* (2010); Gupta *et al., (*2016)	47-80	22-60

Multiple drainage	Tyagi *et al.* (2010)	-	41
Mid-season drainage	Pathak *et al.* (2012)	-	GWP by 33
Intermittent drainage	Adhya *et al.,* (2000); Majumdar, (2003); Pathak et al., (2005)	-	15-88
Intermittent flooding	Mohanty *et al.,* (2017);	-	73-75
Intermittent flooding with single aeration	Gupta et al., (2002)		55
Intermittent flooding with multiple aeration	Gupta et al., (2002)		85

Enhancing water use efficiency, crop yields and mitigation through micro irrigation in rice

Micro irrigation is an effective approach for increasing the water use efficiency and increasing crop yields compared with the inefficient flood irrigation method. Various micro irrigation methods such as surface drip, sub-surface drip, sprinkler, low pressurized system etc., are used in rice. Drip irrigation (Surface and subsurface) has high irrigation efficiency in rice, providing water precisely to the crop roots, reduced the conveyance losses compared to flooding, thus minimised the energy needed for pumping the water. Maximum reduction in GHG emissions were observed in the case of sub-surface drip (36-44%) systems followed by surface drip (17-25%) in rice crops. Subsurface drip systems minimized CO_2 emissions to the extent of 17-44% indicating significant mitigation potential, contributing to yield improvement to the extent of 18-31% and water saving to the extent of 23% compared to the conventional method (Parthasarathi *et al.,* 2021).

Table 6.6. Mitigation of greenhouse gas emissions and impact on crop yields with micro irrigation in comparison to traditional flood method

Micro irrigation system	**% Emission reduction (CO_2 equivalent emissions)**	**%Yield increase**	**Reference**
Sub-surface drip irrigation with 1.0 litre per hour discharge rate emitters in rice	44	31	Parthasarathi *et al., (*2021)
Surface drip irrigation with 1.0 litre per hour discharge rate emitters in rice	25	18	
Sub-surface drip irrigation with 0.6 litre per hour discharge rate emitters in rice	36	26	
Surface drip irrigation with 0.6 litre per hour discharge rate emitters in rice	17	11	

Mitigation through management of groundwater irrigation in rice

India is the largest groundwater user in the world, with an estimated usage of around 248.69bcm and agriculture is the single largest user of water. In India, out of the total 6881 ground water assessment units, 1186 units in various states (17%) have been categorized as ‘over-exploited’, indicating groundwater extraction exceeding the annual replenishable groundwater recharge. In addition, 313 units (5%) are ‘critical’, with groundwater extraction ranging between 90 and 100% of recharge (Central Ground Water Board (CGWB, 2019). The number of groundwater irrigation structures went from 6.2 million in 1986–1987 to 20.5 million in 2013–2014 (Mukherji, 2020). Moreover, the area irrigated by groundwater has increased greatly, while it comprised only 29% of the total irrigated area in 1950-51, and today it accounts for 63% of irrigated area and 90% of withdrawal is for irrigation (Jain et al., 2019). The overexploited areas are mostly concentrated in (i) the north-western part of the country, including parts of Punjab, Haryana, Delhi and western Uttar Pradesh in which significant area is under rice cultivation with groundwater; (ii) the western part of the country, particularly in parts of Rajasthan and Gujarat, where due to the arid climate, groundwater recharge is limited; (iii) the southern part of peninsular India including parts of Karnataka, Andhra Pradesh, Telangana and Tamil Nadu (Saha *et al.,* 2016). Some of the states such as Punjab, Haryana, western Uttar Pradesh have significant areas under rice, where groundwater is used for irrigation on a significant scale. The mitigating options for carbon emissions from groundwater include rationing the electricity supply, adopting micro-irrigation technologies, improving pump efficiency, improving on-farm irrigation efficiency, and managed aquifer recharge, to make groundwater irrigation more energy and carbon efficient (Shah, 2009; Karimi *et.al.,* 2012).

[Placeholder] Box 4: Mitigation in diet shifts and reduced food loss and waste

6.3 Water dependence

As explained in the previous section, the mitigation potential of forests, croplands and grasslands is highly dependent on an intact and functional water cycle. Water is the main limiting factor for vegetation growth in many parts of the world which experience periodic droughts (Smith & Knapp 2001, Knapp et al 2002). With climate change, more frequent and longer periods of drought are expected in these areas, with negative effects on primary production and increased risk of biodiversity loss. Ongoing and projected climate change altogether present substantial risks to the stability of land carbon stocks and sinks of this century (Anderegg et al. 2020). The consequence of a reduced vegetation cover, hence, is a net loss of soil C and in the long-term positive feedback to climate change. Thus, large-scale and destructive shifts in vegetation cover can change global climate conditions, by altering the surface energy budget, leading to deterioration of local water resources (Pielke et al 2002).

Droughts can trigger other disturbances such as promoting occurrences, intensities and frequencies of wildfires (Marti-Roura et al 2011). Recurrent droughts, in combination with fires, affect, in the long term, the soil and water resources of ecosystems that often are critical to overall ecosystem functions and processes (DeBano et al 1998 + REF). The long-term fire effects on soils and water are usually subtle, can persist for years following the fire, or can be permanent as often not only removes aboveground biomass but also decrease local viable seed banks in soils that are essential for ecosystem recovery after a fire (Neary

& Leonard 2020; Shi et al. 2022). Post-drought recovery of an ecosystem is much more rapid where greater levels of biodiversity are conserved than in less diverse areas (Tilman & ElHaddi 1992, Tilman & Downing 1996). In particular, greater ecological diversity means higher resistance to drought because of the complementary use of available water and other resources when compared to communities with low ecological diversity (Fridley 2001).

6.3.1 Forest-based mitigation measures depend on freshwater

Forest-based mitigation measures are fundamentally dependent on a functional water cycle. An altered water cycle risks leading to droughts, floods, and reduced water quality that reduces tree growth and survival, hence decreasing C sequestration. It may also threaten the very existence of a forest ecosystem, thus reducing already existing forest carbon sinks. For instance, tropical forests and savannas are both possible biomes (i.e., "alternative stable states" distinguished mainly through the precipitation regime) under intermediate rainfall conditions (1000 to 2500 mm per year) in regions with mild seasonality (less than seven dry season months) (Staver, Archibald, and Levin 2011). Within this hydroclimatic envelope, the self-amplifying feedbacks of climate change involving increased aridity, droughts, and fire may induce abrupt and potentially irreversible change in biome state (Staver, Archibald, and Levin 2011).

Water availability is, after sunlight, usually the most limiting factor of tree growth. Trees limited by water can be found in many places globally, but the strongest water limitation occurs in the lower to mid latitudes (Fig. 6.X). Afforestation in arid and semi-arid regions is particularly prone to water limitations. For example, afforestated areas in Mongolia have been shown to suffer from water deficit (Z. Wang et al. 2020), and a critical revegetation level in the Loess Plateau is almost (Feng et al. 2016) or already reached (S. Zhang et al. 2018) and may need substantial adjustment (-36 % to + 43 %) in the future depending on uncertainties in climate change, precipitation change, and water demand (Feng et al. 2016). Carbon uptake in tropical forests declines considerably in dry years (Doughty et al. 2015), whereas drought events may cause carbon to release several times larger than the annual carbon sink in tropical forests (Lewis et al. 2011). However, it should be noted that in many boreal zones, water availability may already have replaced energy as the dominant limiting factor (Babst et al. 2019) and in scenarios of severe climate change (RCP 8.5.) increasing temperatures and droughts risk having detrimental effects on tree growth - and thus C sequestration ability. Furthermore, drought events have a disproportionately large impact on mortality rates of large trees (Phillips et al. 2010; Bennett et al. 2015) and therefore a disproportionate impact on carbon emissions and storage (Corlett 2016; J-F Bastin et al. 2015; Fauset et al. 2015). Hence, detailed consideration of water constraints (incl. water demand, hydroclimatic change, planting densities, and tree species selection) is necessary to avoid overestimation of the sustainable level of reforestation and afforestation potential for carbon sequestration.

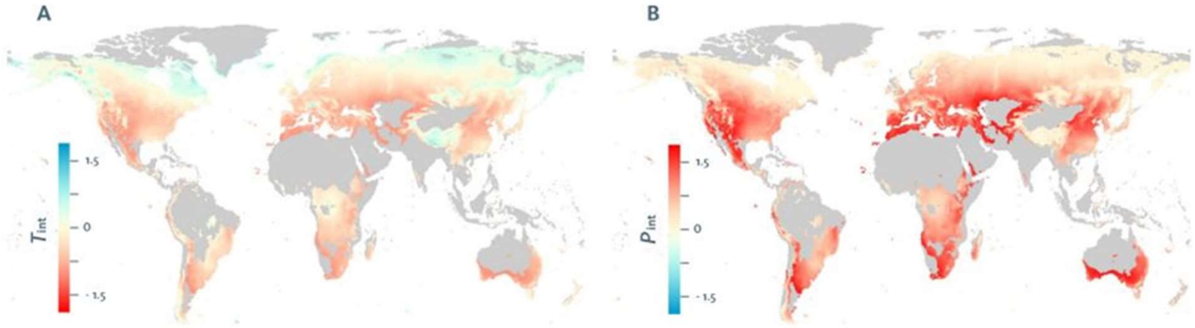

Fig. 6.8. Tree growth responses to climate changes in (A) temperature and (B) precipitation, based on tree-ring data sampled from 2710 sites between the years 1930 and 1960. Red colours indicate strong water constraints and blue colours indicate strong energy constraints. Source: Babst et al. 2019

Plantations often involve fast growing, water intensive tree species (such as most pioneer species) that require high water availability (Silveira et al. 2016; Cao et al. 2016; Zheng et al. 2016). Irrigation is sometimes applied to increase growth rates (Laclau et al. 2005; Stape et al. 2010). Global implementation of bioenergy plantations with subsequent carbon capture and storage (BECCS) required for 1.5°C target scenarios will require water withdrawals for irrigation between ~400 and ~3000 km3 yr−1 (depending on the scenario and the conversion efficiency of the carbon capture and storage process) (Stenzel et al. 2019) (see Chapter 7 for further information on the water implications of bioenergy).

6.3.2 Croplands and grasslands mitigation measures depend on freshwater

The distribution and densities of trees and plants are controlled by the moisture availability of an ecosystem, in turn the vegetation plays a key role in the carbon sequestration and storage. As with forests, the full mitigation potential of land-based mitigation measures can only be reached with an intact water cycle and enough available freshwater. Measures to restore, conserve and sustainably manage vegetation cover and soil carbon stocks depend on freshwater, while they also in many cases – if implemented correctly – can improve water flows and quality. In agriculture, sustainable land-management practices, such as reduced tillage intensity and the use of perennial crops, have the potential to both enhance water use efficiency and preserve soil carbon stocks while also reducing input costs (Beare et al., 1994; Li et al. 2019).

Croplands and grasslands are sensitive to climatic changes and shifts in the local climatic regime, and climate change strongly impact plant species survival and distribution, which in turn increases ecosystem vulnerability, promotes fires and soil degradation, and thus hampers primary production. Climate change has in many places already strongly altered local and regional water cycles, causing changes in precipitation patterns and more frequently occurring and more intense droughts and flooding. These changes have impacted carbon sequestration and storage in agricultural lands, where drought events in some regions have hampered crop production, while in other regions large floods have put agricultural lands under water, causing crop loss, soil erosion, pollution and the spread of invasive species (Warner, 2017).

Drought and land-use change have a direct impact on the carbon source/sink function of a grassland ecosystem, which in turn has a feedback effect on the global climate system. In recent years, the increased intensity and duration of droughts have also dramatically altered the structure and function of grassland ecosystems. Regional gradients in rainfall affects the distributions of major grassland types as well as mean root depth and root productivity, which in turn affect soil organic carbon storage and other soil properties and processes. Grasslands degradation can cause extensive soil erosion especially during extreme events such as flooding (Lal 1995). The fine root system of grasslands stabilizes topsoils that after degradation of grassland species can easily be washed away during heavy rain events or blown away by winds which may also causes major problems for agriculture (Boardman & Vandaele 2010). To mitigate climate change, sustainable land-use and management strategies can strongly influence grassland resistance to environmental impacts such as droughts and wildfires and regulate the carbon storage capacity of grassland soils (Parton et al 1994).

Box 5: Crop production, virtual water & water footprints

Crop production is a water intensive activity; on a global scale, 70% of all water is used in agriculture (FAO 2018). To more accurately represent the amount of water used in agricultural production, Tony Allen coined the concept of Virtual Water (Allan 2003, 2011, 1998), conceptually encapsulating all water utilised during the production process, thus becoming ‘embodied’ in the product.

Through trade in agricultural commodities, virtual water flows through a global intricate web. Many scholars have explored how these ‘virtual water flows’ could be understood in order to improve global water use efficiency in agricultural production, and ease environmental constraints by utilising the best suited production sites (Hoekstra 2003; Hoekstra and Hung 2005; Yang et al. 2006; Zimmer and Renault 2003). Based on this logic, Allan argued that water-scarce nations should import food products that are water intensive in their production as a means to alleviate national water scarcity. Following such thinking could, in theory, reduce the amount of water needed for global agricultural production, and save water on a global scale (Seekell 2011; Yang et al. 2006).

To look at the embedded water in individual agricultural products, the concept of Water Footprints has evolved from discussions around virtual water. Coined in the early 2000s by Arjen Hoekstra (Hoekstra 2003; Hoekstra and Hung 2005), the water footprint of a particular good can be defined as its cumulative virtual water content. The concept has primarily been picked up by companies, seeking to assess the water going into their different products and set quantitative targets to improve water use efficiency per unit of product (Rudebeck 2019).

Despite being conceptually appealing, there are issues with relying too heavily on water footprint assessments to determine the amount of water in a product, and the product’s subsequent water impact. Firstly, the assessment does not account for whether the crop is irrigated or rainfed. Secondly, the same crop may require more or less water depending on in which geographical context it is grown, so the actual footprint may vary a lot depending on location. Finally, if the crop is grown in a water abundant area, a large water footprint does not necessarily imply a negative societal or environmental impact. To use water footprints as a benchmark for more or less positive water practice in agricultural production is therefore problematic.

6.4 Water impacts

6.4.1 Forest-based mitigation measures impact freshwater

Cross-continental impacts. Over time, due to interactions with climate change and other types of land-use changes, the overall effects of afforestation and reforestation on hydroclimate can be complex (Teuling et al. 2019). In comparison to grasslands, agricultural land, and other short vegetation types, forests' relatively higher evapotranspiration rates (particularly during dry periods) also means that they have higher potential to generate the ecosystem service of providing moisture for downwind rainfall (Patrick W. Keys, Wang-Erlandsson, and Gordon 2016). In areas where a large share of the evaporation returns as precipitation over land, see figure 6a (van der Ent et al. 2014), protecting forests may also mean protecting downwind rainfall. Current levels of human deforestation have resulted in lower rates of precipitation in comparison to a scenario of potential pristine vegetation (Wang-Erlandsson et al. 2018). Large-scale tropical deforestation may modify circulation patterns and affect rainfall notably in the mid-latitudes (Lawrence and Vandecar 2015). In both Amazon and Congo rainforests, substantial parts of the rainfall generate from evapotranspiration from the forests themselves. While interception acts as a multiplier of rainfall in the forest water cycle during wet periods, forest transpiration is particularly important for rainfall during dry periods and for buffering against droughts (Wang-Erlandsson et al. 2014; van der Ent et al. 2014; Staal et al. 2018). This recycling of forest moisture means that deforestation-induced reductions in rainfall may lead to cascading and self-amplifying forest loss in downwind regions (Zemp et al. 2017), as well as adverse impacts on crop yields and ecosystems downwind of the rainforests such as in the cerrados in Brazil and the La Plata region in Argentina (Oliveira et al. 2013). Prevention of deforestation in regions that contribute most to downwind forest resilience may, thus, imply multiplied carbon mitigation benefits through prevention of loss in rainfall that is necessary for supporting healthy carbon sequestering ecosystems.

Local to regional impacts. The impacts of afforestation, reforestation and forest restoration on local water yields are complex and context-specific (Ellison et al. 2017; Ulrik Ilstedt et al. 2007)). Forests have higher evapotranspiration compared to shorter vegetation types such as grasslands and shrublands (L. Zhang, Dawes, and Walker 2001). Trees and forests can improve the hydrological functioning of degraded soils, in particular through enhanced soil infiltration capacity and preferential flow (Ulrik Ilstedt et al. 2007; Filoso et al. 2017; Lozano-Baez et al. 2019; Bargués Tobella et al. 2014; Benegas et al. 2014; Bonnesoeur et al. 2019; Leite et al. 2018). Hence, forestation and tree-based restoration of degraded lands may have a less negative impact on groundwater recharge and dry season flows than predicted from most of the available scientific evidence (Zhou et al. 2010; Ogden et al. 2013; Krishnaswamy et al. 2013), in particular under intermediate degrees of tree cover (Ilstedt et al. 2016) as it might be the case in agroforestry and other tree-based mosaic restoration approaches that promote an open tree cover. Moreover, in regions prone to flooding and erosion, afforestation/reforestation from short vegetation types may help reduce such risks (Salvati and Carlucci 2014; Lee et al. 2018; S. Wang et al. 2016). Finally, cloud forest restoration and reforestation in locations exposed to moist winds and frequently covered in clouds and fog, can have positive effects on water yields through increased cloud-water interception (Bruijnzeel and Bruijnzeel 2001; Ghazoul and Sheil 2010; Bruijnzeel, Mulligan, and Scatena 2011).

Measures where trees are planted, such as in forest restoration, afforestation, reforestation and agroforestry, can have large impacts on the regional water cycle. Species with a high demand for freshwater risk having negative impacts on river flows and groundwater, particularly in dry areas and during dry periods (Z. Wang et al. 2020; McVicar et al. 2007; Mu et al. 2007). For instance, a study examining potential improvements in water provision by analysing changes in annual water yield in forest restoration and other forms of forest cover expansion showed an 80 percent yield decrease, as well as an increase in 6% of the cases (Filoso et al. 2017). The use of longer rotation periods and species selection, for instance by promoting tree species that consume less water and/or are more effective at improving soil hydrological functioning, can also be effective in reducing the observed negative impacts of afforestation on streamflow (Scott and Prinsloo 2008; Ferraz, Lima, and Rodrigues 2013). Further improvements in water yields may be achieved through other ecohydrological-based forest management practices such as thinning or pruning, which can also increase the adaptation and resilience of forests to climate change and reduce the risk of fire (Ameztegui et al. 2017; del Campo et al. 2017; Bayala 2002; N. A. Jackson, Wallace, and Ong 2000). Anthropogenic activities in forests, such as excessive livestock grazing or litter collection, can lead to soil degradation and override the positive effects of trees on soil infiltration capacity (Ghimire et al. 2014; Ghimire et al. 2013; Lulandala et al. 2021). Hence, controlling and minimising the impact of these activities, for instance through grazing exclosures, should be a priority.

6.4.2 Croplands and grasslands mitigation measures impact freshwater

An ecosystem's water cycle and carbon cycle are strongly interlinked, for example through the role of the above- and below-ground biomass in carbon cycling. Croplands and grasslands mitigation measures are aimed at improving vegetation cover and thus have a positive influence on soil moisture in several ways; it can reduce the water evaporation by shading the soil and regulating soil temperature, decrease the magnitude of water erosion by reducing the impacts of rainfall, runoff and flood events on the soil, and it can reduce streamflow and sediment export by intercepting runoff and improving water infiltration. For instance, the trees in agroforestry can influence the soils' ability to capture, store and release water, as organic matter from trees can help soil to hold water and improve soil structure and porosity (Benegas et al. 2015).

However, there are also cases where misguided implementation of croplands and grasslands climate mitigation measures can disrupt water flows and reduce freshwater availability, and thus risk causing local water shortage, biodiversity loss, and harm to local communities.
As in forest systems, the species selection is also key for climate mitigation measures in croplands and grazing lands, especially in arid and semiarid regions. Species that are sensitive to water stress or have high demand for water should only be grown in areas that do not experience water stress and periods of drought. In situations where more water demanding species are needed, there are sustainable management options that can reduce water-risks. Agroforestry and other climate-smart integrated farming systems, for instance by using shade crops, crop rotations, cover crops and integrated crop-livestock systems (Kakamoukas et al. 2021; Niggli et al. 2009). Technical measures to improve water use efficiency can also be used, such as micro- or drip-irrigation (Parthasarathi et al., 2021)

6.5 Co-benefits and trade-offs with human well-being and social development goals

The issues of how, where, and why climate mitigation measures are implemented are ultimately questions of governance and politics (see Larson et al. 2021, (Pritchard 2021). Furthermore, addressing such questions must consider the broader political economy and place people at the centre of proposed solutions. The choice of certain mitigation measures often reflects the different political interests and ideas underlying development and the forest sector (Di Gregorio et al. 2017; Brockhaus et al. 2021) resulting in policy measures to reduce deforestation and degradation disproportionately often targeting smallholder and shifting cultivation farmers over political priority for large scale industrial development (Skutsch and Turnhout 2020), see (Ingalls and Dwyer 2016) for the case of Laos, and (Ravikumar et al. 2017) for Peru. A failure to examine the underlying narratives and rationale behind the policy measures and their implications for local equity (Delabre et al. 2020), risks neglecting potential (and politically invisible) trade-offs, missing opportunities for potential synergies and ultimately jeopardising the sustainability of the mitigation measure of choice and resilience of the landscape of interest.

In the context of forests, trade-offs and synergies are most typically conceptualised as being between biodiversity conservation and human well-being or broader development objectives. As such, many recent conservation or mitigation interventions have been designed with a view to both reducing ecosystem degradation (or enhancing forest cover) and simultaneously enhancing local human well-being – so called win-win approaches (Reed et al. 2016). However, as forest-based mitigation measures are implemented at large scales there will more plausibly be a range of outcomes beyond a change in emissions output (Bustamante et al. 2014) and this inevitably affects a vast range of interested stakeholders. Experiences over the last few decades have indeed shown that win-win outcomes are the exception rather than the norm (Christensen, 2004, Sunderland et al. 2008, McShane et al. 2011, Muradian et al. 2013) and interventions more typically result in trade-offs and may incur unintended negative outcomes. Indeed, even initiatives that have been touted as win-wins have, upon closer analysis, been revealed to also generate negative impacts. For example, in Peru an increase in biofuel production was claimed to deliver both environmental (cleaner, renewable fuel source) and well-being (jobs, economic development) benefits but important environmental, institutional, and socio-economic trade-offs were overlooked (Dammert & Canzianni, 2009). In addition, a systematic review (Malkamäki et al. 2018) concludes that tree plantations, often lauded as a win-win approach to livelihoods and mitigation, have had predominantly negative impacts on land (rights and access), livelihoods, and other intertwined social issues globally.

It is important to note that effects of mitigation measures are site-specific and therefore generalising about the types of trade-offs to expect or synergies to try to optimise is challenging. However, in designing such initiatives it can be useful to characterise potential outcomes across the institutional, socio-economic, and environmental dimensions (Bustamante et al. 2014, Reed et al. 2020) and consider how these will impact stakeholders across various scales and over time (i.e., local-regional-national-global). A deeper examination of how such outcomes relate to or address existing issues of inequities or social-environmental injustices will also be critical if these measures are to gain legitimacy and ownership at all scales.

Regions identified as opportunities for forestation measures are not ‘empty’, one-third of the population in the tropical Global South (approx 1.01 billion) live within 8 km of land identified as potential for forest restoration (Erbaugh et al. 2020). Depending on design and the breadth of stakeholder engagement and level of prioritisation to local people, each mitigation measure can, and likely will, result in both trade-offs and synergies across one or more of the institutional, socio-economic, and environmental dimensions. For example, a forest landscape restoration program could contribute to emission reductions but likely also impact on local land tenure and/or create resource use conflicts, food production, local water and soil quality, local adaptive capacity, and conservation of biodiversity. The extent to which these are positively or negatively impacted will depend on the contextual conditions and institutions in place (Larson et al. 2013). Furthermore, trade-offs and synergies can occur both within and between sectors and generate further feedbacks (both site-specific and distant) over time.

Box 6.6. Positive forest conservation in indigenous and tribal territories

A recent study by FAO (FAO and FILAC. 2021), showed that in the Amazon basin, loss of forests in indigenous and tribal territories could have catastrophic consequences for the local and regional climate, resulting in a negative feedback loop that could affect regional rainfall patterns as well as local and global temperatures. These territories have been identified as potential OECMs provided the territories and the Indigenous Peoples and local communities that inhabit them have appropriate legal and non-legal recognition (Jonas et al., 2014). The FAO study also shows that on average, forests in indigenous and tribal territories in Latin America and the Caribbean are much better conserved than other forests, with indigenous territories preventing deforestation equally or even better than non-indigenous protected areas. This is the result of indigenous people’s land management practices that are based on traditional knowledge of forests and the environment. As a final point, the study highlights that to ensure the conservation of forests in Indigenous and tribal people’s territories and address the continuous pressure on these territories, new investment and policy initiatives should include and support: strengthening of communal territorial rights, compensation for environmental services, community forest management, cultural revitalization and traditional knowledge, and finally, territorial governances and stronger indigenous organisations.

6.6 Policy status

Forest and water issues have mostly been discussed in the academic community, focusing mainly on biophysical aspects of forest-water relationships, with a clear gap in the science-policy interface (Springgay et al. 2019). In general, policies that have an impact on or are related to forest-based mitigation measures and take into account water have mostly been developed either in the forest or water sectors without necessarily being thought of as mitigation measures as such. It is only recently, especially with the momentum created by global processes related to climate change action, that policies have been revised or developed addressing, or at least acknowledging, the forest, water and climate link. This means that while there is some advancement in policies related to forest mitigation that take into account water, there is still a lot of work to be done.

The forest-water area of work started gaining momentum in 2002 with the Shiga Declaration on Forests and Water where experts on the topic highlighted the need for more holistic approaches to policies and management of forests and water (FAO 2013). In 2007, the Warsaw Resolution 2 on Forests and Water of the Ministerial Conference on the Protection of Forests in Europe marked another milestone as signatory Parties and the European community committed to work on four areas of concern, one being forests, water and climate change (FAO 2013). This sparked a number of global and regional events up to the present that have catalysed action and discussion with the link between climate change, forests and water featuring prominently (FAO 2013; Springgay et al. 2019).

Although water shortages are a growing problem for rainfed agriculture and livestock, the integration of these concerns into policy frameworks is still slow, even within the agriculture sector. Managing water resources requires coordination and policy coherence across sectors, subsectors in agriculture, and locations, as well as effective governance to manage interdependence and trade-offs between them. Agriculture plays a central role through the landscapes it manages and the water it uses. More coherent strategies are needed across rainfed and irrigated cropland, livestock production systems, forests, and inland fisheries and aquaculture. Incentives are important and payments for environmental services, particularly within watersheds, can play a role in sustaining ecosystem functions (FAO, 2020).

Globally, specific policies that relate to forests and other land uses as mitigation measures have been mostly driven by the UN Framework Convention on Climate Change (UNFCCC) processes. Namely the Kyoto Protocol, the Paris Agreement and most recently, the Koronivia Joint Work on Agriculture (KJWA). The KJWA main aim is to mainstream the unique potential of land systems in tackling climate change by driving transformation in agricultural, forests and food systems, and address the synergies and trade-offs between adaptation, mitigation and land systems productivity. Countries are responsible for implementing the agreements at the national level, for instance through the Nationally Determined Contributions (NDCs) and National Adaptation Policies (NAPs). However, when it comes to mitigation measures that take into account the link between land systems and water, it is important to look beyond the UNFCCC agreements as other global processes have also played a significant role in the advancement of policies and measures that address this link, providing other important entry points. This section explains how policy related measures have evolved to reach the current state and highlight some of the gaps.

6.6.1 Governance frameworks

Global governance frameworks that include land-based mitigation measures that also address water have come from various areas of work such as the implementation of the different conventions and UN processes. These include the UNCCD (Strategic Objectives 1 and 3 in particular), the CBD and its recently expired Aichi targets (targets 5, 7,11, 14 and 15 are particularly relevant) and the Ramsar Convention on Wetlands (Strategic plan goals 1 and 3 and target 12 in particular) to name a few. The United Nations Forum on Forests and its UN Strategic Plan for Forests has relevant thematic areas of work under all its goals such as the contribution of forests to climate change mitigation and adaptation and, the protective functions of forests for soil and water management. However, the most important current instrument is the Paris Agreement under the UNFCCC, which provides a framework to include, update and/or develop land-based mitigation policies that include water as part of the NDC process. It is important to note that as frameworks evolve, they have aimed to align their work with each other and with other global frameworks such as the Sustainable Development Goals (SDGs) (Chapter 3).

To improve the productivity and resilience of land and water resources it is crucial to aim for productive, multifunctional landscapes and good governance considering human rights for a more equitable distribution of water (IPCC 2019). For degraded crop land and soils the SDG 15 “Life on land” and its target 15.3 “By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world” is of direct relevance. LDN involves sustainable land management (SLM) practices to maintain or enhance soil organic carbon, by avoiding or reducing future land degradation while at the same time reversing previous degradation. Farmers can implement the LDN framework while also mitigating climate change by the adoption of SLM approaches and technologies, such as erosion control, SOC sequestration and water conservation (Chotte et al. 2019).

With respect to the forest and land water nexus, a study by (Springgay et al. 2019), evaluated 168 (I)NDCs to look at the extent to which forest and land related water resources management is included. The results showed that 45% of the evaluated (I)NDCs made reference to keywords related to the forest and water nexus, while 57% included agricultural measures within their mitigation sections. Since that study, the NDCs have been updated and a recent study by SIWI shows encouraging results on how NDCs are evolving and becoming more comprehensive (see box 6.7).

Box 6.7. Integration in NDC

See BOX 3.1 in Chapter 3 for background information on the NDC study on which these results are based.

Forests

Forest based policies and measures were included in most enhanced NDC’s and form a significant part of mitigation strategies for many countries. Forest-based mitigation policies and measures were found in 65% of Enhanced NDC’s from Non-Annex 1 countries. In addition, measures that specifically referenced Nature Based Solutions, found in 45% of Non-Annex 1 NDC’s, mostly focussed on increased role of forests, and mangrove forests, especially in terms of their mitigation potential. However, the recognition of the role of water in maintaining forest ecosystems or recognising the connection between water resources and forest management was rare in mitigation sections, even in those parties that acknowledged possible connections between water and climate change within their adaptation sections.

Whilst adaptation sections contain more detail on activities or measures in relation to Forests, mitigation sections often contained generic provisions grouped around six types of activities including reforestation, afforestation and plantations, forest restoration/rehabilitation, sustainable forest management or similar, legal forest protection, and reductions in the rate of deforestation and/or REDD measures. Of those enhanced NDC’s from non-Annex 1 countries that included forest measures within their mitigation sections, reforestation activities were the most frequent activity, followed by sustainable forest management (73%) and restoration/rehabilitation of forest lands (67%). Measures relating to afforestation or plantations were included in 60% of enhanced NDC's, whilst measures relating to reducing the rate of deforestation and/or REDD activities were found in just over 50% of those NDC's that included forest measures. The final type, forest protection, was found in a third (34%) of those NDCs that included forestry measures. One or more forest mitigation measures were found in almost all Sub-Saharan African countries evaluated (35 as of January 2022), whilst most Latin American countries (18 as of January 2022) also include forest mitigation measures.

Very few forest mitigation measures specifically included water components or recognised the role of water in maintaining forest ecosystems or the provision of forest-generated ecosystem services. Reforestation and afforestation can have a significant impact on hydrological systems, but such connections were not raised in mitigation sections. The main exception to this were limited numbers of NDC's that included riparian restoration or mangrove forests within their mitigation sections.

As well as forestry activities, approximately 45% of the enhanced NDC's include measures that would result in a shift from fuelwood or firewood to alternative energy sources and cookware technologies.

Examples of mitigation measures include:

Tajikistan: *Promoting Nature based Solutions, Forest Landscape restoration and other relevant approaches to improve forest conditions.*

Liberia: · *Establish 5 new Protected Areas to complement the existing government commitment to increase forest Protected Areas to 1.5 million ha, ensuring a 3km buffer zone, by 2030 o Reduce emissions by 210 Gg CO2e per year by accelerating the designation of forest Protected Areas.*

Liberia: *Implement an awareness campaign concerning water pollution by logging companies and deploy additional environmental inspectors or agents in the high-risk areas to address logging-related pollution by 2025*

Malawi: *Riparian restoration: Around 36,000 Ha of native species and bamboo to be planted within riparian zones and wetland borders to enable higher ecological productivity and sustainable harvesting.*

South Sudan: *Improve the efficiency of biomass use. South Sudan will focus on improving energy efficiency in the use of biomass, in particular, fuel wood and charcoal in the traditional energy sector*

Croplands and grasslands (Agriculture)

Of the 114 enhanced NDC's evaluated for this report, 57% included agricultural measures within their mitigation sections. However, specific water-related agricultural mitigation measures around croplands and rangelands were relatively uncommon, although they were often more common in adaptation sections. Instead, many enhanced NDC's included generic measures regarding climate smart agriculture, rice production, and improvements in irrigation. In addition to these measures, other measures cited by one or more parties, including soil carbon measures, industrial farming energy efficiency, enteric methane from livestock, reduction of fossil fuel inputs, sustainable land management, rainwater harvesting, and solar powered irrigation pumping. For example, El Salvador, Malawi, and Rwanda noted connections between soil ecosystem and soil conservation measures as providing co-benefits for mitigation.

Close to 65% of enhanced NDC's included mitigation measures in relation to the increased use of biofuels or biomass in their respective emissions targets. These measures were found in multiple sectors, including Energy, Waste, Agriculture, Transport and Forestry. Most of these measures were silent on the main source of biofuel or biomass for energy purposes, but all will have implications for local water resources irrespective of means of generation. Such interactions were not recognised in mitigation sections, except for the enhanced NDC from Tajikistan.

Examples of mitigation measures include:

Albania: *Improved sustainable cropland management: Development of agroforestry is projected to be progressively increasing to 100ha in 2030. Improvement of agricultural soil practices help storing carbon in soils in areas that increase progressively to 20% of cultivated cropland in 2030. In 2030, the application of this measure allows a reduction of the annual emission estimated at -167 kt CO2e compared to the BAU scenario*

Liberia: *Deploy at least 1 solar water pump and/or spring irrigation system for crop irrigation for communal farms with land constraints in each county by 2030.*

Liberia: *Link agricultural development with the National REDD+ Strategy by 2025.*

South Sudan: *Implement initiatives to reduce emissions related to agricultural soils. Agricultural soils are a major emitter of GHGs, contributing more than 50% to total agricultural emissions (in 2015). Thus, introducing measures for reducing soil emissions will be a key aspect for South Sudan.*

Background to the NDCs are found in Chapter 3, section 3.2.1 and box 3.2.

(SIWI/GIZ NDC study (forthcoming))

At the global and regional levels, several initiatives have also been launched to catalyse action on forest and land-based mitigation. Global initiatives include the UN Decade on Ecosystem Restoration (Chapter 3), and the Bonn Challenge, a global initiative aiming to restore 150 million hectares of degraded and deforested landscapes by 2020 and 350 million hectares by 2030 (IUCN, 2020). Another initiative is the New York Declaration on Forests – a political declaration endorsed by numerous actors aiming to cut forest loss in half by 2020 and strive to end it by 2030,

Regional initiatives play a particularly important role as they can provide effective means for regional and transboundary cooperation with actions specifically targeted to address regional and local challenges. Relevant initiatives include, for example the Great Green Wall for the Sahara and the Sahel Initiative (Box X) as well as regional initiatives under the Bonn challenge such as the AFR100, Initiative 20x20, and ECCA30.

6.6.2 Regulatory instruments

Global governance frameworks provide the basis for national and subnational processes that establish regulatory instruments. Their success then also depends on strong national and sub-national enabling environments and inclusive approaches across sectors. These instruments often include integrated land-use or water resources management, land tenure legislation, restrictions in use and access (i.e. protected areas) among others (World Bank, 2021). While many of these instruments may not have been initially developed as climate change mitigation regulatory instruments specifically, they clearly address or have an impact on what we now consider land-based climate mitigation measures.

While there have been vast improvements in the management of protected areas, other effective area-based conservation measures (OECMs) are increasingly being considered as an alternative. They, have been recognized and encouraged under the CBD since 2010 and are defined under CBD Decision 14/8 as "a geographically defined area other than a Protected Area, which is governed and managed in ways that achieve positive and sustained long-term outcomes for the in-situ conservation of biodiversity, with associated ecosystem functions and services and where applicable, cultural, spiritual, socio–economic, and other locally relevant values." Recognition of OECMs in legal national frameworks and supporting legal mechanisms that, for example, limit industrial development or natural resource extractions, can prove to be effective regulatory instruments in the case of key areas for the conservation and restoration of forests that takes into account water.

While relevant regulatory instruments may not necessarily be framed as climate mitigation instruments per se, those instruments developed under different sectors as well as alternatives to traditional instruments have the potential to be effective. Their success depends on the inclusion of other relevant sectors, recognition and inclusion of all relevant actors and on management that uses a landscape approach. Furthermore, regulatory instruments should also be accompanied by economic and financial mechanisms and incentives, which will be discussed in the next section.

6.6.3 Economic and financial mechanisms

Effective climate mitigation strategies and policies should always integrate regulative (sticks), and informational (sermons) instruments with financial mechanisms (so-called carrots). This section gives a brief overview of those policies and Market-Based Instruments (MBIs) that can be classified as "carrots", such as rewards, incentives, payments, and blend-finance for ensuring the success of forest-based mitigation measures.

Most of the literature on MBIs and incentive-based public instruments focuses on the broad concept of Payments for Environmental Services (PES), which are defined as "transfers of resources between social actors, which aim to create incentives to align individual and/or collective land use decisions with the social interest in the management of natural resources" (Muradian et al. 2010). It has been demonstrated that PES approaches allow for greater integration and cooperation between agroforestry and water sectors as these instruments are often based on a multi-stakeholder dialogue between land managers and other resource dependent industries (such as utilities, hydropower, irrigation, etc.). Furthermore, it has been suggested that

PES schemes, for instance, could go hand in hand with strengthening local governments and community management (FAO, IUFRO and USDA, 2021), offering win-win solutions and aligning public, private and civil society interests around natural resource management. REDD+ (Reducing Emissions from Deforestation and Forest Degradation Mechanisms) is one example where forest conservation and restoration as a climate change mitigation measure is incorporated in what could be considered a PES scheme for carbon.

PES schemes may be classified depending on the role that the public sector plays: it can intervene both as buyer (like in the case of agro-environmental schemes, in the EU, and in the US, etc.) and/or as legal actor, providing a legal framework and/or with obligation to offset emission or other resource uses (scope taxes, Emission Trading Scheme, etc.). Where the state does not intervene, there are instances where the private market steps in (with voluntary carbon and ecosystem services markets). Mainly, the PES markets that provide funding for forest mitigation are related to carbon, water and biodiversity offsetting, being the main ecosystem services required by the private sector. Table 6.6 summarises the main funding mechanisms available to fund forest and land-based mitigation measures.

Table 6.6. Funding instruments for ecosystem services generated by forest and land-based mitigation measures

Type	**Instrument**	**Description**
Public regulated	Regulated carbon market	Carbon markets can be divided into two types: regulated compliance and voluntary (see below). The regulated market is used by companies and governments that are required by law to account and offset their GHG emissions. Regulated compliance markets have legally binding compliance standards for emission reductions, which can be at the international, national, regional level. Examples of regulated markets include UNFCCC's REDD+ mechanism and the three mechanisms of the Kyoto Protocol: The Clean Development Mechanism (CDM), the Joint Implementation (JI) and the European Union's Emissions Trading Scheme (ETS).
	Agro - environmental schemes	These are well-known schemes in the US, Europe, and Australia. Their institution tracks back in the '70, before the PES concept was conceived. They are typically national/continental incentives schemes, with little targeting and additionality. However, they constitute the main scheme type for western countries, often incentivizing tree planting, tree hedgerows maintenance, fire control and sustainable forest management for water quality. Some 90% of EU funding for forests comes from the European Agricultural Fund for Rural Development (EAFRD).
	Water-forest scope taxes	Scope taxes can be used to generate funding from natural resource exploitation. These mechanisms are based on the adoption of water charges/fees in the hydropower and drinking water sector, but not only. The funding generated is often associated with an obligation to reinvest the revenues into forest and catchment restoration activities. This is the case of the several water funds in Latin America and Asia which rely on water charges as their funding source for catchment and forest restoration.

Private	Voluntary carbon markets	Voluntary carbon markets emerged in the mid-1990s, are self-regulated, and exist separately from carbon markets set up by governments in response to the 1997 Kyoto Protocol. It usually works with private forest carbon certification standards (such as Gold Standard, VCS, VERRA, etc) where reforestation projects certified a certain amount of CO2 tons stored by producing "carbon credits", and carbon brokers are then placing these credits on the private market for CO2 offsetting. In 2021, the voluntary carbon credit market exceeded $1 billion for the first time and is projected to increase 15-fold by 2030 (Ecosystem Marketplace 2021).
	Voluntary certification schemes	Consists of schemes whereby producers send a signal to consumers that environmental impacts are positive (in relative terms) and consequently gain a premium on the market price. The most known are the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) with respectively 230 and 330 million hectares of certified forest area. Since 2018 FSC has developed a specific procedure to verify ecosystem services impacts and allow for registered sponsorship and claims. A recent WWF report highlights the new FSC strategy on PES development (WWF 2022) which relies on short ecosystem services value chains, building direct connection between forest managers and communities and sponsors.
	Investment blended funds	These are private funds such as environmentally focused bonds, loans, equity, funded by impact or philanthropic investors that invest on green-grey infrastructure projects in order to fulfil their impact-oriented missions, however, expecting a return on the investment that generates from cost saving from reduced operational costs. These funds may also be public, such as the Land Degradation Neutrality and the IEB - Natural Capital Financing Facility. These funds are often coupled with technical assistance and grants funds, to deliver blended-finance programs.

Policy makers, scientific literature, and the market are proliferating a considerable number of initiatives, case studies, and best practices. Despite this, relevant, effective, and large-scale instruments based on the private markets are often missing or still in the development stage. Nevertheless, the trend is clear, especially after the last COP26, where within the Glasgow Leaders' Declaration on Forests and Land Use, 141 countries representing 90% of global forests agreed to "significantly increase finance and strengthen financial commitments from both public and private sources". The COP26 has also opened the room to private carbon credits generated by the private market to offset within the regulated market. The European Commission will release by 2022 its carbon farming initiative, regulating public and private land-based carbon markets in the EU. While, many private initiatives, such as Science Based Targets Network are leveraging new market demand for water and biodiversity offsetting under the nature positive concept. This will play an important point in busting the future of these instruments, with the hope that these incentives will build on strong benefit sharing mechanisms, ecosystem services ownership, ensuring effective positive impacts on the ground.

6.7 Potential implications for governance

Globally, recognition and implementation of land-based mitigation measures that take into account water in the governance frameworks, regulatory instruments, and financial mechanisms is moving towards more holistic and multisectoral approaches as shown in section 6.6. While it is encouraging to see advancements in this direction, there are gaps that remain to be addressed, especially when it comes to actual national and local implementation. To close these gaps, it is necessary to strengthen the science – policy interface by using the most up to date science and considering the complex and potentially cross-scale feedbacks of land-based mitigation measures, and potential trade-offs and synergies among different benefits and constraints. This can take the form of system thinking and integrated landscape management approaches (Seddon et al. 2020; Farooqi et al. 2020).

Furthermore, it is important to consider the relationship between land-based mitigation measures with water at different scales of governance and management. At local and other sub-national scales, policies and management plans often account for water impacts of forest-based mitigation measures on blue water (e.g., as part of catchment management or national adaptation programmes of actions (Pramova et al. 2012)) but other aspects of water-related dependency, impact, and feedback are typically not considered (Ellison et al. 2017). An example of this is proposals of integrative management and consideration of atmospheric processes. These are not yet linked to policy and governance in climate mitigation contexts and more work is needed to assess how these concepts can be usefully integrated into existing mitigation measures such as REDD+, CDM, and NDCs.

As global governance frameworks move forward, it is also important to take all available information and tools into consideration to improve indicators, methodologies and monitoring to achieve global goals. For example, the process of refining the SDG indicators and their methodology is an evolving process that needs to be reviewed periodically in accordance with UN General Assembly Resolution A/RES/71/313 ("A/RES/71/313 - E - A/RES/71/313 -Desktop" n.d.). This provides an opportunity for monitoring methodologies for the SDG indicators to be further developed and to fill in gaps. In the case of NDCs, they are reviewed every five years (UNFCCC, 2022). This provides an opportunity to build and improve on previous NDCs and to revise national policies, so targets are met.

6.8 Conclusions and future outlook

Land systems mitigation measures can be cost-effective and generate substantial win-wins among water, biodiversity, social, and other sustainability goals. However, depending on the context, time-scale considerations, and implementation processes, there are substantial risks for unrealised mitigation potential and negative impacts on other water, biodiversity, social equality, and other sustainability goals (Sect. 6.5). As such, there is a need to ensure systems thinking in the management and governance of land systems mitigation measures that holistically account for interconnected issues of e.g., water constraints, land availability, carbon sequestration, biodiversity implications, local livelihoods and regional development.

Land-based climate mitigation measures have a high carbon emission reduction potential that are intrinsically linked to the water cycle. Of these mitigation measures, the prevention of deforestation and forest and land degradation has historically received the greatest attention and investment. However, while commitments to reducing deforestation remain high on the global policy agenda, the past decade has seen an increasing focus on forest and landscape restoration through processes under various Multilateral Environmental Agreements and other initiatives such as the Bonn Challenge and the UN Decade on

Ecosystem Restoration. So far, these measures and mechanisms have been mainly focused on carbon management, however, more recently there is an increasing understanding of the importance of accounting for water and biodiversity co-benefits, which are becoming more and more important, both from an ecological point of view, and for the market demand, in relation to current nature-positive targets.

Nevertheless, while many of the international agreements highlight the importance of co-benefits and natural resource-based livelihoods, the mitigation measures and instruments often do not adequately consider local social-ecological dynamics in these changing land systems. In most cases, factors such as risks to the regional water cycle and dynamical dependence on freshwater resources are surprisingly insufficiently analysed and quantified in the creation and negotiation of the mitigation policies. Similarly, poorly understood is how the changing forest system and water cycles are interlinked with adaptive livelihood strategies.

All land-based mitigation measures must account for the water risks and water cycle changes that ongoing climate change already present, including lowering of agricultural productivity regionally and globally, irreversible damage to biodiversity, and reversion of forest carbon sinks into carbon sources. All measures must also account for their social and environmental justice implications to local populations. Land-based mitigation measures are also integral to non-local drivers to forest-land-water systems, and require consideration of interlinkages through for example trade, migration, hydroclimatic teleconnections, and international frameworks. This chapter has shown the importance of adopting large-scale system dynamics thinking and an integrated approach to land-based mitigation in order to achieve the best possible climate and sustainability benefits. Any financial mechanisms and public policy should support holistic approaches, avoiding the "carbon tunnel" and integrating water and biodiversity conservation as key goals instead as co-benefits, ensuring benefit sharing with local communities.

6.9 References

Adhya, T.K., Linquist, B., Searchinger, T., Wassmann, R. and Yan, X., 2014. Wetting and drying: Reducing greenhouse gas emissions and saving water from rice production. Instalment 8 of "creating a sustainable food future". World Resources Institute working paper.

Agriculture situation in India. 2021. Directorate of Economics and Statistics. Department of Agriculture & Farmers Welfare, Ministry of Agriculture & Farmers Welfare, Government of India. 78 (6): p.56.

Ameztegui, Aitor, Antoine Cabon, Miquel De Cáceres, and Lluís Coll. 2017. "Managing Stand Density to Enhance the Adaptability of Scots Pine Stands to Climate Change: A Modelling Approach." *Ecological Modelling* 356 (July): 141–50.

APEDA, 2021. https://apeda.gov.in/apedawebsite/organic/data. htm#Summary_Statistics_2021

Arora, Vivek K., and Alvaro Montenegro. 2011. "Small Temperature Benefits Provided by Realistic Afforestation Efforts." *Nature Geoscience* 4 (8): 514–18.

Babst, Flurin, Olivier Bouriaud, Benjamin Poulter, Valerie Trouet, Martin P. Girardin, and David C. Frank. 2019. "Twentieth Century Redistribution in Climatic Drivers of Global Tree Growth." *Science Advances* 5 (1): eaat4313.

Bala, G., K. Caldeira, M. Wickett, T. J. Phillips, D. B. Lobell, C. Delire, and A. Mirin. 2007. "Combined Climate and Carbon-Cycle Effects of Large-Scale Deforestation." *Proceedings of the National Academy of Sciences of the United States of America* 104 (16): 6550–55.

Bárcena, T. G., L. P. Kiær, L. Vesterdal, H. M. Stefánsdóttir, P. Gundersen, and B. D. Sigurdsson. 2014. "Soil Carbon Stock Change Following Afforestation in Northern Europe: A Meta-Analysis." *Global Change Biology* 20 (8): 2393–2405.

Bargués Tobella, A., H. Reese, A. Almaw, J. Bayala, A. Malmer, H. Laudon, and U. Ilstedt. 2014. "The Effect of

Trees on Preferential Flow and Soil Infiltrability in an Agroforestry Parkland in Semiarid Burkina Faso.” *Water Resources Research* 50 (4): 3342–54.

Bartlett, Jesamine, Graciela M. Rusch, Magni Olsen Kyrkjeeide, Hanno Sandvik, and Jenni Nordén. 2020. *Carbon Storage in Norwegian Ecosystems (revised Edition)*. NINA Rapport. Norsk Institutt for Naturforskning (NINA).

Basavalingaiah, K., Ramesha, Y.M., Paramesh, V., Rajanna, G.A., Jat, S.L., Dhar Misra, S., Kumar Gaddi, A., Girisha, H.C., Yogesh, G.S., Raveesha, S. and Roopa, T.K., 2020. Energy budgeting, data envelopment analysis and greenhouse gas emission from rice production system: A case study from puddled transplanted rice and direct-seeded rice system of Karnataka, India. Sustainability, 12(16), p.6439

Bastin, Jean-Francois, Yelena Finegold, Claude Garcia, Danilo Mollicone, Marcelo Rezende, Devin Routh, Constantin M. Zohner, and Thomas W. Crowther. 2019. “The Global Tree Restoration Potential.” *Science* 365 (6448): 76–79.

Bastin, J-F, N. Barbier, M. Réjou-Méchain, A. Fayolle, S. Gourlet-Fleury, D. Maniatis, T. de Haulleville, et al. 2015. “Seeing Central African Forests through Their Largest Trees.” *Scientific Reports* 5 (August): 13156.

Bayala, Jules. 2002. “Tree Crown Pruning as a Management Tool to Enhance the Productivity of Parklands in West Africa.” University of Wales, Bangor,. https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.247299.

“Becoming #GenerationRestoration.” n.d. Accessed December 6, 2021. https://www.unep.org/interactive/ecosystem-restoration-people-nature-climate/en/index.php.

Benegas, L., U. Ilstedt, O. Roupsard, J. Jones, and A. Malmer. 2014. “Effects of Trees on Infiltrability and Preferential Flow in Two Contrasting Agroecosystems in Central America.” *Agriculture, Ecosystems & Environment* 183 (January): 185–96.

Bennett, Amy C., Nathan G. McDowell, Craig D. Allen, and Kristina J. Anderson-Teixeira. 2015. “Larger Trees Suffer Most during Drought in Forests Worldwide.” *Nature Plants* 1 (September): 15139.

Berger, Markus, Ruud van der Ent, Stephanie Eisner, Vanessa Bach, and Matthias Finkbeiner. 2014. “Water Accounting and Vulnerability Evaluation (WAVE): Considering Atmospheric Evaporation Recycling and the Risk of Freshwater Depletion in Water Footprinting.” *Environmental Science & Technology* 48 (8): 4521–28.

Bernal, Blanca, Lara T. Murray, and Timothy R. H. Pearson. 2018. “Global Carbon Dioxide Removal Rates from Forest Landscape Restoration Activities.” *Carbon Balance and Management* 13 (1): 22.

Betts, R. A. 2000. “Offset of the Potential Carbon Sink from Boreal Forestation by Decreases in Surface Albedo.” *Nature* 408 (6809): 187–90.

Bjørn, Anders, Sarah Sim, Henry King, Manuele Margni, Andrew D. Henderson, Sandra Payen, and Cécile Bulle. 2020. “A Comprehensive Planetary Boundary-Based Method for the Nitrogen Cycle in Life Cycle Assessment: Development and Application to a Tomato Production Case Study.” *The Science of the Total Environment* 715 (May): 136813.

Bhatia, A., Jain, N. and Pathak, H., 2013. Methane and nitrous oxide emissions from Indian rice paddies, agricultural soils and crop residue burning. Greenhouse Gases: Science and Technology, 3(3), pp.196-211

Bonnesoeur, Vivien, Bruno Locatelli, Manuel R. Guariguata, Boris F. Ochoa-Tocachi, Veerle Vanacker, Zhun Mao, Alexia Stokes, and Sarah-Lan Mathez-Stiefel. 2019. “Impacts of Forests and Forestation on Hydrological Services in the Andes: A Systematic Review.” *Forest Ecology and Management* 433 (February): 569–84.

Bossio, D. A., S. C. Cook-Patton, P. W. Ellis, J. Fargione, J. Sanderman, P. Smith, S. Wood, et al. 2020. “The Role of Soil Carbon in Natural Climate Solutions.” *Nature Sustainability*. https://doi.org/10.1038/s41893-020-0491-z.

Brancalion, Pedro H. S., Aidin Niamir, Eben Broadbent, Renato Crouzeilles, Felipe S. M. Barros, Angelica M. Almeyda Zambrano, Alessandro Baccini, et al. 2019. “Global Restoration Opportunities in Tropical Rainforest Landscapes.” *Science Advances*. https://doi.org/10.1126/sciadv.aav3223.

Bruijnzeel, L. A., and L. A. Bruijnzeel. 2001. “Hydrology of Tropical Montane Cloud Forests: A Reassessment.” Unknown. https://doi.org/10.22004/AG.ECON.47849.

Bruijnzeel, L. A., Mark Mulligan, and Frederick N. Scatena. 2011. “Hydrometeorology of Tropical Montane Cloud Forests: Emerging Patterns.” *Hydrological Processes* 25 (3): 465–98.

Busch, Jonah, Jens Engelmann, Susan C. Cook-Patton, Bronson W. Griscom, Timm Kroeger, Hugh Possingham, and Priya Shyamsundar. 2019. “Potential for Low-Cost Carbon Dioxide Removal through Tropical Reforestation.” *Nature Climate Change* 9 (6): 463–66.

Campo, Antonio D. del, M. González-Sanchis, A. Lidón, A. García-Prats, C. Lull, I. Bautista, G. Ruíz-Pérez, and F. Francés. 2017. “Ecohydrological-Based Forest Management in Semi-Arid Climate.” In *Ecosystem Services of Headwater Catchments*, edited by Josef Křeček, Martin Haigh, Thomas Hofer, Eero Kubin, and Catrin Promper, 45–57. Cham: Springer International Publishing.

Cao, Shixiong, Junze Zhang, Li Chen, and Tingyang Zhao. 2016. "Ecosystem Water Imbalances Created during Ecological Restoration by Afforestation in China, and Lessons for Other Developing Countries." *Journal of Environmental Management* 183 (Pt 3): 843–49.

Carrijo D.R., Lundy M.E., Linquist B.A. 2017. Rice yields and water use under alternate wet and drying irrigation: A meta-analysis. Field Crops Research 203:173-180. DOI: 10.1016/j.fcr.2016.12.002

Ceci, Paolo. 2013. *Forests and Water: International Momentum and Action*. Food and Agriculture Organization.

Chazdon, Robin L., Pedro H. S. Brancalion, Lars Laestadius, Aoife Bennett-Curry, Kathleen Buckingham, Chetan Kumar, Julian Moll-Rocek, Ima Célia Guimarães Vieira, and Sarah Jane Wilson. 2016. "When Is a Forest a Forest? Forest Concepts and Definitions in the Era of Forest and Landscape Restoration." *Ambio* 45 (5): 538–50.

Chakraborty, D., Ladha, J.K., Rana, D.S., Jat, M.L., Gathala, M.K., Yadav, S., Rao, A.N., Ramesha, M.S. and Raman, A., 2017. A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production. Scientific reports, 7(1), pp.1-11. https://doi.org/10.1038/s41598-017-09742-9.

Chazdon, Robin L., Pedro H. S. Brancalion, David Lamb, Lars Laestadius, Miguel Calmon, and Chetan Kumar. 2017. "A Policy-driven Knowledge Agenda for Global Forest and Landscape Restoration." *Conservation Letters* 10 (1): 125–32.

Cook-Patton, Susan C., David Shoch, and Peter W. Ellis. 2021. "Dynamic Global Monitoring Needed to Use Restoration of Forest Cover as a Climate Solution." *Nature Climate Change* 11 (5): 366–68.

Corlett, Richard T. 2016. "The Impacts of Droughts in Tropical Forests." *Trends in Plant Science* 21 (7): 584–93.

Cotecna, 2021. https://www.cotecna.com/en/locations/india.

Crouzeilles, R., Beyer, H.L., Monteiro, L.M., et al. 2020. Achieving cost-effective landscape-scale forest restoration through targeted natural regeneration. Conservation letters, 13(3), p.e12709.

Cuni-Sanchez, Aida, Martin J. P. Sullivan, Philip J. Platts, Simon L. Lewis, Rob Marchant, Gérard Imani, Wannes Hubau, et al. 2021. "High Aboveground Carbon Stock of African Tropical Montane Forests." *Nature* 596 (7873): 536–42.

Deelstra J., Nagothu U.S., Kakumanu K.R., Kaluvai Y.R., Kallam S.R. 2018. Enhancing water productivity using alternative rice growing practices: a case study from Southern India. The Journal of Agricultural Science 156(5): 673-679. DOI: 10.1017/S0021859618000655

Delabre, Izabela, Emily Boyd, Maria Brockhaus, Wim Carton, Torsten Krause, Peter Newell, Grace Y. Wong, and Fariborz Zelli. 2020. "Unearthing the Myths of Global Sustainable Forest Governance." *Global Sustainability* 3. https://doi.org/10.1017/sus.2020.11.

Dey, A. and Dinesh, R., 2020. Rice and wheat production in India: An overtime study on growth and instability. Journal of Pharmacognosy and Phytochemistry, 9(2), pp.158-161.

Di Gregorio, Monica, Caleb Tyrell Gallemore, Maria Brockhaus, Leandra Fatorelli, and Efrian Muharrom. 2017. "How Institutions and Beliefs Affect Environmental Discourse: Evidence from an Eight-Country Survey on REDD+." *Global Environmental Change: Human and Policy Dimensions* 45 (July): 133–50.

Doelman, Jonathan C., Elke Stehfest, Detlef P. van Vuuren, Andrzej Tabeau, Andries F. Hof, Maarten C. Braakhekke, David E. H. J. Gernaat, et al. 2020. "Afforestation for Climate Change Mitigation: Potentials, Risks and Trade-Offs." *Global Change Biology* 26 (3): 1576–91.

Doughty, Christopher E., D. B. Metcalfe, C. A. J. Girardin, F. F. Amezquita, L. Durand, W. Huaraca Huasco, J. E. Silva-Espejo, et al. 2015. "Source and Sink Carbon Dynamics and Carbon Allocation in the Amazon Basin: TROPICAL FOREST SOURCE, SINK DYNAMICS." *Global Biogeochemical Cycles* 29 (5): 645–55.

Duchelle, Amy E., Gabriela Simonet, William D. Sunderlin, and Sven Wunder. 2018. "What Is REDD+ Achieving on the Ground?" *Current Opinion in Environmental Sustainability* 32 (June): 134–40.

Duque, Alvaro, Miguel A. Peña, Francisco Cuesta, Sebastián González-Caro, Peter Kennedy, Oliver L. Phillips, Marco Calderón-Loor, et al. 2021. "Mature Andean Forests as Globally Important Carbon Sinks and Future Carbon Refuges." *Nature Communications* 12 (1): 2138.

Elias, M., Kandel, M., Mansourian, S., Meinzen-Dick, R., Crossland, M., Joshi, D., Kariuki, J., Lee, L.C., McElwee, P., Sen, A. and Sigman, E., 2022. Ten people-centered rules for socially sustainable ecosystem restoration. Restoration Ecology, 30(4), p.e13574.

Elliott, S., D. Blakesley, and K. Hardwick. 2013. "Restoring Tropical Forests: A Practical Guide." https://bioone.org/journalArticle/Download?urlId=10.1505%2F146554813806948503.

Ellison, David, Cindy E. Morris, Bruno Locatelli, Douglas Sheil, Jane Cohen, Daniel Murdiyarso, Victoria Gutierrez, et al. 2017. "Trees, Forests and Water: Cool Insights for a Hot World." *Global Environmental Change: Human and Policy Dimensions* 43 (March): 51–61.

Ent, R. J. van der, L. Wang-Erlandsson, P. W. Keys, and H. H. G. Savenije. 2014. "Contrasting Roles of Interception and Transpiration in the Hydrological Cycle – Part 2: Moisture Recycling." *Earth System Dynamics*. https://doi.org/10.5194/esd-5-471-2014.

Erb, Karl-Heinz, Thomas Kastner, Christoph Plutzar, Anna Liza S. Bais, Nuno Carvalhais, Tamara Fetzel, Simone Gingrich, et al. 2018. "Unexpectedly Large Impact of Forest Management and Grazing on Global Vegetation Biomass." *Nature* 553 (7686): 73–76.

Eriksson, Mats, Lotta Samuelson, Linnéa Jägrud, Eskil Mattsson, Thorsten Celander, Anders Malmer, Klas Bengtsson, et al. 2018. "Water, Forests, People: The Swedish Experience in Building Resilient Landscapes." *Environmental Management* 62 (1): 45–57.

Farley, Kathleen A., Esteban G. Jobbagy, and Robert B. Jackson. 2005. "Effects of Afforestation on Water Yield: A Global Synthesis with Implications for Policy." *Global Change Biology* 11 (10): 1565–76.

FAO. 2022. Grazing with trees – A silvopastoral approach to managing and restoring drylands. FAO Forestry Paper, No. 187. Rome.

FAO. 2020. The State of Food and Agriculture 2020. Overcoming water challenges in agriculture. Rome. https://doi.org/10.4060/cb1447en

FAO; IUFRO; USDA; (2021). A guide to forest–water management. In A guide to forest–water management. FAO, USDA and IUFRO. https://doi.org/10.4060/CB6473EN

Farooqi, Tanzeel Javaid Aini, Xuhua Li, Zhen Yu, Shirong Liu, and Osbert Jianxin Sun. 2020. "Reconciliation of Research on Forest Carbon Sequestration and Water Conservation." *Journal of Forest Economics* 3 (May): 553.

Fauset, Sophie, Michelle O. Johnson, Manuel Gloor, Timothy R. Baker, Abel Monteagudo M, Roel J. W. Brienen, Ted R. Feldpausch, et al. 2015. "Hyperdominance in Amazonian Forest Carbon Cycling." *Nature Communications* 6 (April): 6857.

Feng, Xiaoming, Bojie Fu, Shilong Piao, Shuai Wang, Philippe Ciais, Zhenzhong Zeng, Yihe Lü, et al. 2016. "Revegetation in China's Loess Plateau Is Approaching Sustainable Water Resource Limits." *Nature Climate Change* 6 (11): 1019–22.

Ferraz, Silvio F. B., Walter de Paula Lima, and Carolina Bozetti Rodrigues. 2013. "Managing Forest Plantation Landscapes for Water Conservation." *Forest Ecology and Management* 301 (August): 58–66.

Fiedler, Stephanie, Traute Crueger, Roberta D'Agostino, Karsten Peters, Tobias Becker, David Leutwyler, Laura Paccini, et al. 2020. "Simulated Tropical Precipitation Assessed across Three Major Phases of the Coupled Model Intercomparison Project (CMIP)." *Monthly Weather Review*. https://doi.org/10.1175/mwr-d-19-0404.1.

Filac. 2021. "Forest Governance by Indigenous and Tribal Peoples: An Opportunity for Climate Action in Latin America and the Caribbean." Food and Agriculture Organization of the United Nations (FAO) Santiago, Chile.

Filoso, Solange, Maíra Ometto Bezerra, Katherine C. B. Weiss, and Margaret A. Palmer. 2017. "Impacts of Forest Restoration on Water Yield: A Systematic Review." *PloS One* 12 (8): e0183210.

Fisher, Rosie A., Charles D. Koven, William R. L. Anderegg, Bradley O. Christoffersen, Michael C. Dietze, Caroline E. Farrior, Jennifer A. Holm, et al. 2018. "Vegetation Demographics in Earth System Models: A Review of Progress and Priorities." *Global Change Biology* 24 (1): 35–54.

Fleischman, F., Coleman, E., Fischer, H., Kashwan, P., Pfeifer, M., Ramprasad, V., Rodriguez Solorzano, C. and Veldman, J.W., 2022. Restoration prioritization must be informed by marginalized people. Nature, 607(7918), pp.E5-E6.

Food and Agriculture Organization. 2020. *Global Forest Resources Assessment 2020: Main Report*. 2nd ed. Global Forest Resources Assessment (FRA). Rome, Italy: Food & Agriculture Organization of the United Nations (FAO).

Fuss, Sabine, William F. Lamb, Max W. Callaghan, Jérôme Hilaire, Felix Creutzig, Thorben Amann, Tim Beringer, et al. 2018. "Negative emissions—Part 2: Costs, Potentials and Side Effects." *Environmental Research Letters: ERL [Web Site]* 13 (6): 063002.

Ghazoul, Jaboury, and Douglas Sheil. 2010. *Tropical Rain Forest Ecology, Diversity, and Conservation*. London, England: Oxford University Press.

Ghimire, Chandra Prasad, Mike Bonell, L. Adrian Bruijnzeel, Neil A. Coles, and Maciek W. Lubczynski. 2013. "Reforesting Severely Degraded Grassland in the Lesser Himalaya of Nepal: Effects on Soil Hydraulic Conductivity and Overland Flow Production." *Journal of Geophysical Research. Earth Surface* 118 (4): 2528–

45.

Ghimire, Chandra Prasad, L. Adrian Bruijnzeel, Mike Bonell, Neil Coles, Maciek W. Lubczynski, and Don A. Gilmour. 2014. "The Effects of Sustained Forest Use on Hillslope Soil Hydraulic Conductivity in the Middle Mountains of Central Nepal." *Ecohydrology* 7 (2): 478–95.

Grainger, Alan, Louis R. Iverson, Gregg H. Marland, and Anantha Prasad. 2019. "Comment on 'The Global Tree Restoration Potential.'" *Science*. https://doi.org/10.1126/science.aay8334.

Green, Julia K., Sonia I. Seneviratne, Alexis M. Berg, Kirsten L. Findell, Stefan Hagemann, David M. Lawrence, and Pierre Gentine. 2019. "Large Influence of Soil Moisture on Long-Term Terrestrial Carbon Uptake." *Nature* 565 (7740): 476–79.

Griscom, Bronson W., Justin Adams, Peter W. Ellis, Richard A. Houghton, Guy Lomax, Daniela A. Miteva, William H. Schlesinger, et al. 2017. "Natural Climate Solutions." *Proceedings of the National Academy of Sciences of the United States of America* 114 (44): 11645–50.

Gupta, D.K., Bhatia, A., Kumar, A., Das, T.K., Jain, N., Tomer, R., Malyan, S.K., Fagodiya, R.K., Dubey, R. and Pathak, H., 2016. Mitigation of greenhouse gas emission from rice–wheat system of the Indo-Gangetic plains: Through tillage, irrigation and fertilizer management. Agriculture, Ecosystems & Environment, 230, pp.1-9

Gupta, P.K., Sharma, C., Bhattacharya, S. and Mitra, A.P., 2002. Scientific basis for establishing country greenhouse gas estimates for rice-based agriculture: An Indian case study. Nutrient Cycling in Agroecosystems, 64(1), pp.19-31.

Hapase, D.G., A.N. Mankar; A.N. Salunkhe; V.M. Salokhe; Gajendra Singh and S.G. Illangantileke (1992) Techno- economic evaluation of drip irrigation for sugarcane crop. In Proceedings of an International Agricultural Engineering Conference, held in Bangkok, Thailand on 7-10 December, 1992, Vol. III, pp. 897-904.

Harris, Nancy L., David A. Gibbs, Alessandro Baccini, Richard A. Birdsey, Sytze de Bruin, Mary Farina, Lola Fatoyinbo, et al. 2021. "Global Maps of Twenty-First Century Forest Carbon Fluxes." *Nature Climate Change* 11 (3): 234–40.

Houghton, Richard A., and Alexander A. Nassikas. 2018. "Negative Emissions from Stopping Deforestation and Forest Degradation, Globally." *Global Change Biology* 24 (1): 350–59.

Högberg, P., Ceder, L.A., Astrup, R., Binkley, D., Dalsgaard, L., Egnell, G., Filipchuk, A., Genet, H., Ilintsev, A., Kurz, W.A. and Laganière, J., 2021. Sustainable boreal forest management challenges and opportunities for climate change mitigation. The Swedish Forest Agency

Hubau, Wannes, Simon L. Lewis, Oliver L. Phillips, Kofi Affum-Baffoe, Hans Beeckman, Aida Cuní-Sanchez, Armandu K. Daniels, et al. 2020. "Asynchronous Carbon Sink Saturation in African and Amazonian Tropical Forests." *Nature* 579 (7797): 80–87.

Ilstedt, U., A. Bargués Tobella, H. R. Bazié, J. Bayala, E. Verbeeten, G. Nyberg, J. Sanou, et al. 2016. "Intermediate Tree Cover Can Maximize Groundwater Recharge in the Seasonally Dry Tropics." *Scientific Reports* 6 (February): 21930.

Ilstedt, Ulrik, Anders Malmer, Elke Verbeeten, and Daniel Murdiyarso. 2007. "The Effect of Afforestation on Water Infiltration in the Tropics: A Systematic Review and Meta-Analysis." *Forest Ecology and Management* 251 (1-2): 45–51.

Ingalls, Micah L., and Michael B. Dwyer. 2016. "Missing the Forest for the Trees? Navigating the Trade-Offs between Mitigation and Adaptation under REDD." *Climatic Change* 136 (2): 353–66.

IPCC. 2019. "Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems."

IPCC 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change." Shukla, P. R., Skea, J., Slade, R., et al. (eds) Cambridge University Press: Cambridge University Press: Cambridge, UK and New York, NY, USA

Jackson, N. A., J. S. Wallace, and C. K. Ong. 2000. "Tree Pruning as a Means of Controlling Water Use in an Agroforestry System in Kenya." *Forest Ecology and Management* 126 (2): 133–48.

Jackson, Robert B., Esteban G. Jobbágy, Roni Avissar, Somnath Baidya Roy, Damian J. Barrett, Charles W. Cook, Kathleen A. Farley, David C. le Maitre, Bruce A. McCarl, and Brian C. Murray. 2005. "Trading Water for Carbon with Biological Carbon Sequestration." *Science* 310 (5756): 1944–47.

Jain, N., Dubey, R., Dubey, D.S., Singh, J., Khanna, M., Pathak, H and Bhatia, A. 2014. Mitigation of greenhouse gas emission with system of rice intensification in the Indo-Gangetic Plains. *Paddy and Water Environment*. 12(3):355-363

Jain R., Kishore P., Singh D. K. (2019). Irrigation in India: Status, challenges and options. Journal of Soil and Water Conservation 18(4): 354-363. DOI: 10.5958/2455-7145.2019.00050.X

Kakraliya S.K., Jat H.S, Singh I., Sapkota T.B., Singh L.K., Sutaliya J.M., Sharma P.C., Jat R.D., Choudhary M., Santiago L.R., Jat M.L. 2018. Performance of portfolios of climate smart agriculture practices in a rice-wheat system of western Indo-Gangetic plains. Agricultural Water Management 202: 122-132. DOI: 10.1016/j.agwat.2018.02.020

Karimi, P., Qureshi, A.S., Bahramloo, R. and Molden, D., 2012. Reducing carbon emissions through improved irrigation and groundwater management: A case study from Iran. Agricultural water management, 108, pp.52-60.

Kaur, J. and Singh, A., 2017. Direct seeded rice: Prospects, problems/constraints and researchable issues in India. Current agriculture research Journal, 5(1): 13.

.Keune, J., and D. G. Miralles. 2019. “A Precipitation Recycling Network to Assess Freshwater Vulnerability: Challenging the Watershed Convention.” *Water Resources Research* 55 (11): 9947–61.

Keys, Patrick W., Lan Wang-Erlandsson, and Line J. Gordon. 2016. “Revealing Invisible Water: Moisture Recycling as an Ecosystem Service.” *PloS One* 11 (3): e0151993.

Keys, Patrick W., Lan Wang-Erlandsson, Line J. Gordon, Victor Galaz, and Jonas Ebbesson. 2017. “Approaching Moisture Recycling Governance.” *Global Environmental Change*. https://doi.org/10.1016/j.gloenvcha.2017.04.007.

Keys, P. W., R. J. van der Ent, L. J. Gordon, H. Hoff, R. Nikoli, and H. H. G. Savenije. 2012. “Analyzing Precipitationsheds to Understand the Vulnerability of Rainfall Dependent Regions.” *Biogeosciences*. https://doi.org/10.5194/bg-9-733-2012.

Khosa, M.K., Sidhu, B.S. and Benbi, D.K., 2010. Effect of organic materials and rice cultivars on methane emission from rice field. Journal of Environmental Biology, 31(3): 281-285

Khokhar, T., 2017. World Bank blog post, based on Food and Agriculture Organization, AQUASTAT data. https://blogs.worldbank.org/opendata/chart-globally-70-freshwater-used-agriculture

Koch, Alexander, Chris Brierley, and Simon L. Lewis. 2021. “Effects of Earth System Feedbacks on the Potential Mitigation of Large-Scale Tropical Forest Restoration.” *Biogeosciences* 18 (8): 2627–47.

Koch, Alexander, Wannes Hubau, and Simon L. Lewis. 2021. “Earth System Models Are Not Capturing Present-day Tropical Forest Carbon Dynamics.” *Earth’s Future* 9 (5). https://doi.org/10.1029/2020ef001874.

Krause, Torsten, and Tobias Dan Nielsen. 2014. “The Legitimacy of Incentive-Based Conservation and a Critical Account of Social Safeguards.” *Environmental Science & Policy* 41 (August): 44–51.

Krishnaswamy, Jagdish, Michael Bonell, Basappa Venkatesh, Bekal K. Purandara, K. N. Rakesh, Sharachchandra Lele, M. C. Kiran, Veerabasawant Reddy, and Shrinivas Badiger. 2013. “The Groundwater Recharge Response and Hydrologic Services of Tropical Humid Forest Ecosystems to Use and Reforestation: Support for the ‘infiltration-Evapotranspiration Trade-off Hypothesis.’” *Journal of Hydrology* 498 (August): 191–209.

Laclau, Jean-Paul, Jacques Ranger, Philippe Deleporte, Yann Nouvellon, Laurent Saint-André, Serge Marlet, and Jean-Pierre Bouillet. 2005. “Nutrient Cycling in a Clonal Stand of Eucalyptus and an Adjacent Savanna Ecosystem in Congo.” *Forest Ecology and Management*. https://doi.org/10.1016/j.foreco.2005.02.028.

Lamb, David. 2018. “Undertaking Large-Scale Forest Restoration to Generate Ecosystem Services: Landscape Restoration and Ecosystem Services.” *Restoration Ecology* 26 (4): 657–66.

Law, B. E., E. Falge, L. Gu, D. D. Baldocchi, P. Bakwin, P. Berbigier, K. Davis, et al. 2002. “Environmental Controls over Carbon Dioxide and Water Vapor Exchange of Terrestrial Vegetation.” *Agricultural and Forest Meteorology* 113 (1): 97–120.

Lawrence, Deborah, and Karen Vandecar. 2015. “Effects of Tropical Deforestation on Climate and Agriculture.” *Nature Climate Change* 5 (1): 27–36.

Lee, Jongyeol, Chul-Hee Lim, Gang Sun Kim, Anil Markandya, Sarwat Chowdhury, Sea Jin Kim, Woo-Kyun Lee, and Yowhan Son. 2018. “Economic Viability of the National-Scale Forestation Program: The Case of Success in the Republic of Korea.” *Ecosystem Services* 29 (February): 40–46.

Leite, Pedro A. M., Eduardo S. de Souza, Eduardo S. dos Santos, Rafael J. Gomes, José R. Cantalice, and Bradford P. Wilcox. 2018. “The Influence of Forest Regrowth on Soil Hydraulic Properties and Erosion in a Semiarid Region of Brazil.” *Ecohydrology* 11 (3): e1910.

Lewis, Simon L., Paulo M. Brando, Oliver L. Phillips, Geertje M. F. van der Heijden, and Daniel Nepstad. 2011. “The

2010 Amazon Drought." *Science* 331 (6017): 554.

Lewis, Simon L., David P. Edwards, and David Galbraith. 2015. "Increasing Human Dominance of Tropical Forests." *Science* 349 (6250): 827–32.

Lewis, Simon L., Edward T. A. Mitchard, Colin Prentice, Mark Maslin, and Ben Poulter. 2019. "Comment on 'The Global Tree Restoration Potential.'" *Science*. https://doi.org/10.1126/science.aaz0388.

Lewis, Simon L., Charlotte E. Wheeler, Edward T. A. Mitchard, and Alexander Koch. 2019. "Restoring Natural Forests Is the Best Way to Remove Atmospheric Carbon." *Nature* 568 (7750): 25–28.

Li, Yue, Shilong Piao, Laurent Z. X. Li, Anping Chen, Xuhui Wang, Philippe Ciais, Ling Huang, et al. 2018. "Divergent Hydrological Response to Large-Scale Afforestation and Vegetation Greening in China." *Science Advances* 4 (5): eaar4182.

Lozano-Baez, Sergio E., Miguel Cooper, Paula Meli, Silvio F. B. Ferraz, Ricardo Ribeiro Rodrigues, and Thomas J. Sauer. 2019. "Land Restoration by Tree Planting in the Tropics and Subtropics Improves Soil Infiltration, but Some Critical Gaps Still Hinder Conclusive Results." *Forest Ecology and Management* 444 (July): 89–95.

Lundmark, Tomas, Bishnu Chandra Poudel, Gustav Stål, Annika Nordin, and Johan Sonesson. 2018. "Carbon Balance in Production Forestry in Relation to Rotation Length." *Canadian Journal of Forest Research. Journal Canadien de La Recherche Forestiere* 48 (6): 672–78.

Luyssaert, Sebastiaan, Guillaume Marie, Aude Valade, Yi-Ying Chen, Sylvestre Njakou Djomo, James Ryder, Juliane Otto, et al. 2018. "Trade-Offs in Using European Forests to Meet Climate Objectives." *Nature* 562 (7726): 259–62.

Mackey, Brendan, Cyril F. Kormos, Heather Keith, William R. Moomaw, Richard A. Houghton, Russell A. Mittermeier, David Hole, and Sonia Hugh. 2020. "Understanding the Importance of Primary Tropical Forest Protection as a Mitigation Strategy." *Mitigation and Adaptation Strategies for Global Change* 25 (5): 763–87.

Majumdar, D., 2003. Methane and nitrous oxide emission from irrigated rice fields: Proposed mitigation strategies. Current Science, 1317-1326.

Malkamäki, Arttu, Dalia D'Amato, Nicholas J. Hogarth, Markku Kanninen, Romain Pirard, Anne Toppinen, and Wen Zhou. 2018. "A Systematic Review of the Socio-Economic Impacts of Large-Scale Tree Plantations, Worldwide." *Global Environmental Change: Human and Policy Dimensions* 53 (November): 90–103.

Mathias, J.M. and Thomas, R.B., 2021. Global tree intrinsic water use efficiency is enhanced by increased atmospheric CO2 and modulated by climate and plant functional types. Proceedings of the National Academy of Sciences, 118(7), p.e2014286118.

Mechiche-Alami, A., O'Byrne, D., Tengberg, A., & Olsson, L. (2022). Evaluating the scaling potential of sustainable land management projects in the Sahelian Great Green Wall countries. Environmental Research Letters, 17(8).

Meera SN, Kumar RM, Muthuraman P, Rao LVS, Viraktamath BC (2014) Important Rice growing ecologies. A handbook of package of practices for rice. Directorate of Rice Research, Book No. 80/2014. pp 13–14

Mohanty, S.R., Bandeppa, G.S., Dubey, G., Ahirwar, U., Patra, A.K. and Bharati, K., 2017. Methane oxidation in response to iron reduction-oxidation metabolism in tropical soils. European Journal of Soil Biology, 78, pp.75-81

Mohanty S, Tripathi R, Shahid M, Kumar A, Thilagam VK, Nayak AK (2013) Rice ecosystems in India. Crop Production Division, Central Rice Research Institute, Cuttack.

Mukherji A. 2020. Sustainable Groundwater Management in India Needs a Water-Energy-Food Nexus Approach. Applied Economic Perspectives and Policy. DOI: 10.1002/aepp.13123

Narayanamoorthy, A. (1996), Impact of drip irrigation on consumption of water and electricity. Asian Economic Review, 38(3): 350-364.

Mayer, Mathias, Cindy E. Prescott, Wafa E. A. Abaker, Laurent Augusto, Lauric Cécillon, Gabriel W. D. Ferreira, Jason James, et al. 2020. "Tamm Review: Influence of Forest Management Activities on Soil Organic Carbon Stocks: A Knowledge Synthesis." *Forest Ecology and Management* 466 (June): 118127.

McVicar, Tim R., Lingtao Li, Tom G. Van Niel, Lu Zhang, Rui Li, Qinke Yang, Xiaoping Zhang, et al. 2007. "Developing a Decision Support Tool for China's Re-Vegetation Program: Simulating Regional Impacts of Afforestation on Average Annual Streamflow in the Loess Plateau." *Forest Ecology and Management* 251 (1-2): 65–81.

Moomaw, William R., Susan A. Masino, and Edward K. Faison. 2019. "Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good." *Frontiers in Forests and Global Change* 2: 27.

Mu, Xingmin, Lu Zhang, Tim R. McVicar, Basang Chille, and Peng Gau. 2007. “Analysis of the Impact of Conservation Measures on Stream Flow Regime in Catchments of the Loess Plateau, China.” *Hydrological Processes* 21 (16): 2124–34.

O’byrne, D., Mechiche-Alami, A., Tengberg, A., & Olsson, L. (2022). The Social Impacts of Sustainable Land Management in Great Green Wall Countries: An Evaluative Framework Based on the Capability Approach. Land, 11(3).

O’Connor, John C., Stefan C. Dekker, Arie Staal, Obbe A. Tuinenburg, Karin T. Rebel, and Maria J. Santos. 2021. “Forests Buffer against Variations in Precipitation.” *Global Change Biology*, July. https://doi.org/10.1111/gcb.15763.

Ogden, Fred L., Trey D. Crouch, Robert F. Stallard, and Jefferson S. Hall. 2013. “Effect of Land Cover and Use on Dry Season River Runoff, Runoff Efficiency, and Peak Storm Runoff in the Seasonal Tropics of Central Panama.” *Water Resources Research* 49 (12): 8443–62.

Oliveira, Leydimere J. C., Marcos H. Costa, Britaldo S. Soares-Filho, and Michael T. Coe. 2013. “Large-Scale Expansion of Agriculture in Amazonia May Be a No-Win Scenario.” *Environmental Research Letters: ERL [Web Site]* 8 (2): 024021.

Ontl, Todd A., Maria K. Janowiak, Christopher W. Swanston, Jad Daley, Stephen Handler, Meredith Cornett, Steve Hagenbuch, Cathy Handrick, Liza Mccarthy, and Nancy Patch. 2019. “Forest Management for Carbon Sequestration and Climate Adaptation.” *Journal of Forestry* 118 (1): 86–101.

Oo AZ, Sudo S, Inubushi K, Chellappan U, Yamamoto A, Ono K, Mano M, Hayashida S, Koothan V, Osawa T, Terao Y. 2018. Mitigation potential and yield-scaled global warming potential of early-season drainage from a rice paddy in Tamil Nadu, India. Agronomy 8(10): 202.

Palanichamy N.V., Palanisamy, K., and T.R. Shanmugam. 2002. Economic performance of drip irrigation in coconut farmers in Coimbatore. Agricultural Economics Research Review, Conference Issue, pp. 40- 48.

Parthasarathi, T., Vanitha, K., Mohandass, S. and Vered, E., 2021. Mitigation of methane gas emission in rice by drip irrigation. F1000Research, 8(2023), p.2023.

Pathak H, Chakrabarti B, Bhatia A, Jain N and Aggarwal PK. 2012. Potential and cost of low carbon technologies in rice and wheat systems: A case study for the Indo- Gangetic Plains In: Pathak H and Aggarwal PK (Eds.) Low Carbon Technologies for Agriculture: A Study on Rice and Wheat Systems in the Indo-Gangetic Plains. Indian Agricultural Research Institute, New Delhi, 12-40 pp.

Pathak H, Li C, Wassmann R. 2005. Greenhouse gas emissions from Indian rice fields: calibration and upscaling using the DNDC model. Biogeosciences Discussions, European Geosciences Union 2(1):77– 102.

Pathak H, Sankhyan S, Dubey DS, Bhatia A and Jain N. 2013. Dry direct-seeding of rice for mitigating GHG emission: field experimentation and simulation. Paddy Water Environ 11: 593–601.

Pathak H., Tewari A.N., Dubey D.S., Mina U., Singh V.K., Jain N., Bhatia A. 2011. Direct-seeded rice: Potential, performance, and problems – A review. Current Advances in Agricultural Sciences 3(2): 77-88.

Paul, K. I., P. J. Polglase, J. G. Nyakuengama, and P. K. Khanna. 2002. “Change in Soil Carbon Following Afforestation.” *Forest Ecology and Management*. https://doi.org/10.1016/s0378-1127(01)00740-x.

Phelps, J., D. A. Friess, and E. L. Webb. 2012. “Win–win REDD+ Approaches Belie Carbon–biodiversity Trade-Offs.” *Biological Conservation* 154 (October): 53–60.

Phillips, Oliver L., Geertje van der Heijden, Simon L. Lewis, Gabriela López-González, Luiz E. O. C. Aragão, Jon Lloyd, Yadvinder Malhi, et al. 2010. “Drought-Mortality Relationships for Tropical Forests.” *The New Phytologist* 187 (3): 631–46.

Pörtner, H.O., Scholes, R.J., Agard, J., et al. 2021. IPBES-IPCC co-sponsored workshop report on biodiversity and climate change; IPBES and IPCC. DOI:10.5281/zenodo.4782538

Pramova, Emilia, Bruno Locatelli, Maria Brockhaus, and Sandra Fohlmeister. 2012. “Ecosystem Services in the National Adaptation Programmes of Action.” *Climate Policy* 12 (4): 393–409.

Rajkishore SK, Doraisamy P, Subramanian KS, Maheswari M. 2013. Methane emission patterns and their associated soil microfora with SRI and conventional systems of rice cultivation in Tamil Nadu, India. Taiwan Water Conserv 61(4):126–134

Rao, A.N., Wani, S.P., Ramesha, M.S. and Ladha, J.K., 2017. Rice production systems. In Rice Production Worldwide (pp. 185-205). Springer, Cham.

Rao KS, Sharma SK, Singh SP, Sharma NK, Mishra GN, Saha S. 2008. Sustainable cropping systems for different rice ecologies. In: Singh DP, Dani RC, Rao KS, Nayak SK, Panda D, Dash RN, Mishra AK, Ghosh A (eds) Rice research priorities and strategies for second green revolution.

Ravikumar, Ashwin, Robin R. Sears, Peter Cronkleton, Mary Menton, and Matías Pérez-Ojeda del Arco. 2017. "Is Small-Scale Agriculture Really the Main Driver of Deforestation in the Peruvian Amazon? Moving beyond the Prevailing Narrative." *Conservation Letters* 10 (2): 170–77.

Rights, Resources Initiative, and Others. 2015. "Protected Areas and the Land Rights of Indigenous Peoples and Local Communities: Current Issues and Future Agenda." *Washington, DC: Rights and Resources Initiative*.

Roriz, Pedro Augusto Costa, and Philip Martin Fearnside. 2015. "A construção do Código Florestal Brasileiro e as diferentes perspectivas para a proteção das florestas." *Novos Cadernos NAEA* 18 (2). https://doi.org/10.5801/ncn.v18i2.1866.

Saha, D., Shekhar, S., Ali, S., Vittala, S.S. and Raju, N.J., 2016. Recent hydrogeological research in India. In Proc. Indian Natl. Sci. Acad. 82 (3). pp. 787-803.

Salvati, Luca, and Margherita Carlucci. 2014. "Zero Net Land Degradation in Italy: The Role of Socioeconomic and Agro-Forest Factors." *Journal of Environmental Management* 145 (December): 299–306.

Sasaki, Nophea, and Francis E. Putz. 2009. "Critical Need for New Definitions of 'forest' and 'forest Degradation' in Global Climate Change Agreements." *Conservation Letters*. https://doi.org/10.1111/j.1755-263x.2009.00067.x.

Schaeffer, M., B. Eickhout, M. Hoogwijk, B. Strengers, D. van Vuuren, R. Leemans, and T. Opsteegh. 2006a. "CO2and Albedo Climate Impacts of Extratropical Carbon and Biomass Plantations." *Global Biogeochemical Cycles*. https://doi.org/10.1029/2005gb002581.

———. 2006b. "CO 2 and Albedo Climate Impacts of Extratropical Carbon and Biomass Plantations : CLIMATE IMPACTS OF CARBON AND BIOMASS PLANTATIONS." *Global Biogeochemical Cycles* 20 (2). https://doi.org/10.1029/2005GB002581.

Scharlemann, Jörn P. W., Edmund V. J. Tanner, Roland Hiederer, and Valerie Kapos. 2014. "Global Soil Carbon: Understanding and Managing the Largest Terrestrial Carbon Pool." *Carbon Management* 5 (1): 81–91.

Schwartzman, Stephan, André Villas Boas, Katia Yukari Ono, Marisa Gesteira Fonseca, Juan Doblas, Barbara Zimmerman, Paulo Junqueira, et al. 2013. "The Natural and Social History of the Indigenous Lands and Protected Areas Corridor of the Xingu River Basin." *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 368 (1619): 20120164.

Scott, David F., and F. W. Prinsloo. 2008. "Longer-Term Effects of Pine and Eucalypt Plantations on Streamflow." *Water Resources Research* 44 (7). https://doi.org/10.1029/2007wr006781.

Seddon, Nathalie, Alexandre Chausson, Pam Berry, Cécile A. J. Girardin, Alison Smith, and Beth Turner. 2020. "Understanding the Value and Limits of Nature-Based Solutions to Climate Change and Other Global Challenges." *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 375 (1794): 20190120.

Seidl, Rupert, Dominik Thom, Markus Kautz, Dario Martin-Benito, Mikko Peltoniemi, Giorgio Vacchiano, Jan Wild, et al. 2017. "Forest Disturbances under Climate Change." *Nature Climate Change* 7 (June): 395–402.

Shah, T., 2009. Climate change and groundwater: India's opportunities for mitigation and adaptation. Environmental Research Letters, 4(3), p.035005

Shah, T., Rajan, A., Rai, G.P., Verma, S. and Durga, N., 2018. Solar pumps and South Asia's energy-groundwater nexus: exploring implications and reimagining its future. Environmental Research Letters, 13(11), p.115003

Sharma, S.K., Singh, Y.V., Tyagi, S and Bhatia, A., 2016. Influence of rice varieties, nitrogen management and planting methods on methane emission and water productivity. Paddy and water environment. 14(2):325-333.

Singh, S.K., Bharadwaj, V., Thakur, T.C., Pachauri, S.P., Singh, P.P. and Mishra, A.K., 2009. Influence of crop establishment methods on methane emission from rice fields. Current Science, pp.84-89.

Sheil, D., Bargués-Tobella, A., Ilstedt, U., et al. 2019. Forest restoration: Transformative trees. Science, 366(6463), pp.316-317.

Shi, Y.F., Shi, S.H., Jiang, Y.S. and Liu, J., 2022. A global synthesis of fire effects on soil seed banks. Global Ecology and Conservation, 36, p.e02132.

Shiyani R.L., D. B. Kuchhadiya and M.V. Patat (1999), Economic impact of drip irrigation technology on cotton growers of Saurashtra region. Agricultural Situation in India, 56 (7): 407-412.

Shukla, P. R., J. Skea, R. Slade, R. van Diemen, E. Haughey, J. Malley, M. Pathak, and J. Portugal Pereira. 2019. "Technical Summary." In *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, edited by P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H-O Pörtner, D. C. Roberts, P. Zhai, et al. In Press.

Silveira, Luis, Pablo Gamazo, Jimena Alonso, and Leticia Martínez. 2016. "Effects of Afforestation on Groundwater Recharge and Water Budgets in the Western Region of Uruguay: Afforestation and Its Effects on Groundwater Recharge and Water Budget." *Hydrological Processes* 30 (20): 3596–3608.

Skidmore, Andrew K., Tiejun Wang, Kees de Bie, and Petter Pilesjö. 2019. "Comment on 'The Global Tree Restoration Potential.'" *Science*. https://doi.org/10.1126/science.aaz0111.

Skutsch, Margaret, and Esther Turnhout. 2020. "REDD+: If Communities Are the Solution, What Is the Problem?" *World Development* 130 (104942): 104942.

Sloan, T. J., Richard John Payne, A. Russell Anderson, Clifton Bain, Steve Chapman, Neil Cowie, Peter Gilbert, et al. 2018. "Peatland Afforestation in the UK and Consequences for Carbon Storage." *Mires and Peat*. http://aura.abdn.ac.uk/handle/2164/12513.

Sonntag, Sebastian, Julia Pongratz, Christian H. Reick, and Hauke Schmidt. 2016. "Reforestation in a High-CO 2 World-Higher Mitigation Potential than Expected, Lower Adaptation Potential than Hoped for : POTENTIAL OF REFORESTATION IN MPI-ESM." *Geophysical Research Letters* 43 (12): 6546–53.

Springgay, Elaine, Sara Casallas Ramirez, Sally Janzen, and Vitor Vannozzi Brito. 2019. "The Forest–Water Nexus: An International Perspective." *Forests, Trees and Livelihoods* 10 (10): 915.

Staal, Arie, Ingo Fetzer, Lan Wang-Erlandsson, Joyce H. C. Bosmans, Stefan C. Dekker, Egbert H. van Nes, Johan Rockström, and Obbe A. Tuinenburg. 2020. "Hysteresis of Tropical Forests in the 21st Century." *Nature Communications* 11 (1): 4978.

Staal, Arie, Obbe A. Tuinenburg, Joyce H. C. Bosmans, Milena Holmgren, Egbert H. van Nes, Marten Scheffer, Delphine Clara Zemp, and Stefan C. Dekker. 2018. "Forest-Rainfall Cascades Buffer against Drought across the Amazon." *Nature Climate Change* 8 (6): 539–43.

Stape, Jose Luiz, Dan Binkley, Michael G. Ryan, Sebastiao Fonseca, Rodolfo A. Loos, Ernesto N. Takahashi, Claudio R. Silva, et al. 2010. "The Brazil Eucalyptus Potential Productivity Project: Influence of Water, Nutrients and Stand Uniformity on Wood Production." *Forest Ecology and Management* 259 (9): 1684–94.

Staver, A. Carla, Sally Archibald, and Simon A. Levin. 2011. "The Global Extent and Determinants of Savanna and Forest as Alternative Biome States." *Science* 334 (6053): 230–32.

Stenzel, Fabian, Dieter Gerten, Constanze Werner, and Jonas Jägermeyr. 2019. "Freshwater Requirements of Large-Scale Bioenergy Plantations for Limiting Global Warming to 1.5 °C." *Environmental Research Letters: ERL [Web Site]* 14 (8): 084001.

Strassburg, Bernardo B. N., Alvaro Iribarrem, Hawthorne L. Beyer, Carlos Leandro Cordeiro, Renato Crouzeilles, Catarina C. Jakovac, André Braga Junqueira, et al. 2020. "Global Priority Areas for Ecosystem Restoration." *Nature* 573 (October): 582.

Suryavanshi, P., Singh, Y.V., Prasanna, R., Bhatia, A. and Shivay, Y.S. 2013. Pattern of methane emission and water productivity under different methods of rice crop establishment. *Paddy and Water Environment.* 11(1):321-329.

Terrer, C., R. P. Phillips, B. A. Hungate, J. Rosende, J. Pett-Ridge, M. E. Craig, K. J. van Groenigen, et al. 2021. "A Trade-off between Plant and Soil Carbon Storage under Elevated CO2." *Nature* 591 (7851): 599–603.

Teuling, Adriaan J., Emile A. G. de Badts, Femke A. Jansen, Richard Fuchs, Joost Buitink, Anne J. Hoek van Dijke, and Shannon M. Sterling. 2019. "Climate Change, Reforestation/afforestation, and Urbanization Impacts on Evapotranspiration and Streamflow in Europe." *Hydrology and Earth System Sciences* 23 (9): 3631–52.

Thompson, Ian D., Manuel R. Guariguata, Kimiko Okabe, Carlos Bahamondez, Robert Nasi, Victoria Heymell, and Cesar Sabogal. 2013. "An Operational Framework for Defining and Monitoring Forest Degradation." *Ecology and Society* 18 (2). http://www.jstor.org/stable/26269330.

Tyagi, L., Kumari, B. and Singh, S.N., 2010. Water management—A tool for methane mitigation from irrigated paddy fields. Science of the Total Environment, 408(5), pp.1085-1090.

Unccd. 2020. "The Great Green Wall Implementation Status and Way Ahead to 2030 Advanced Version." In . United Nations Convention to Combat Desertification Bonn, Germany.

"UN Decade on Restoration." n.d. Accessed December 6, 2021. https://www.decadeonrestoration.org/about-un-decade.

Vatta K., Sidhu R.S., Upmanu L., Birthal P.S., Taneja G., Kaur B., Devineni N., MacAlister C. 2018. Assessing the economic impact of a low-cost water-saving irrigation technology in Indian Punjab: the tensiometer. Water International 43(2): 305-321. DOI: 10.1080/02508060.2017.1416443.

Veldman, Joseph W., Julie C. Aleman, Swanni T. Alvarado, T. Michael Anderson, Sally Archibald, William J. Bond, Thomas W. Boutton, et al. 2019. "Comment on 'The Global Tree Restoration Potential.'" *Science*. https://doi.org/10.1126/science.aay7976.

Veldman, Joseph W., Fernando A. O. Silveira, Forrest D. Fleischman, Nataly L. Ascarrunz, and Giselda Durigan. 2017. "Grassy Biomes: An Inconvenient Reality for Large-Scale Forest Restoration? A Comment on the Essay by Chazdon and Laestadius." *American Journal of Botany*.

Wang-Erlandsson, L., R. J. van der Ent, L. J. Gordon, and H. H. G. Savenije. 2014. "Contrasting Roles of Interception and Transpiration in the Hydrological Cycle – Part 1: Temporal Characteristics over Land." *Earth System Dynamics*. https://doi.org/10.5194/esd-5-441-2014.

Wang-Erlandsson, L., Ingo Fetzer, Patrick W. Keys, Ruud J. van der Ent, Hubert H. G. Savenije, and Line J. Gordon. 2018. "Remote Land Use Impacts on River Flows through Atmospheric Teleconnections." *Hydrol. Earth Syst. Sci.* 22 (August): 4311–28.

Wang, Shuai, Bojie Fu, Shilong Piao, Yihe Lü, Philippe Ciais, Xiaoming Feng, and Yafeng Wang. 2016. "Reduced Sediment Transport in the Yellow River due to Anthropogenic Changes." *Nature Geoscience*. https://doi.org/10.1038/ngeo2602.

Wang, Ziyu, Daoli Peng, Duanyang Xu, Xiaoyu Zhang, and Yue Zhang. 2020. "Assessing the Water Footprint of Afforestation in Inner Mongolia, China." *Journal of Arid Environments* 182 (November): 104257.

Warner, B. P., Schattman, R. E., & Hatch, C. (2017). Farming the floodplain: Ecological and agricultural tradeoffs and opportunities in river and stream governance in New England's changing climate. In Case Studies in the Environment. DOI: 10.1525/cse.2017.sc.512407

Weng, Wei, Luís Costa, Matthias K. B. Lüdeke, and Delphine C. Zemp. 2019. "Aerial River Management by Smart Cross-Border Reforestation." *Land Use Policy*. https://doi.org/10.1016/j.landusepol.2019.03.010.

Wilkinson, S. L., P. A. Moore, M. D. Flannigan, B. M. Wotton, and J. M. Waddington. 2018. "Did Enhanced Afforestation Cause High Severity Peat Burn in the Fort McMurray Horse River Wildfire?" *Environmental Research Letters: ERL [Web Site]* 13 (1): 014018.

Wurtzebach, Zachary, Thorkil Casse, Henrik Meilby, Martin R. Nielsen, and Anders Milhøj. 2019. "REDD+ Policy Design and Policy Learning: The Emergence of an Integrated Landscape Approach in Vietnam." *Forest Policy and Economics* 101 (April): 129–39.

WWF 2022. Vallauri, D., Darteyron, L.-E., & Laurans, Y. (2022). PAYING FORESTERS TO PROVIDE ECOSYSTEM SERVICES? PRINCIPLES, ANALYSIS OF RESULTS TO DATE IN THE FSC PROCEDURE AND THE WAY FORWARD. Published by WWF.

Zemp, Delphine Clara, Carl-Friedrich Schleussner, Henrique M. J. Barbosa, Marina Hirota, Vincent Montade, Gilvan Sampaio, Arie Staal, Lan Wang-Erlandsson, and Anja Rammig. 2017. "Self-Amplified Amazon Forest Loss due to Vegetation-Atmosphere Feedbacks." *Nature Communications* 8 (March): 14681.

Zhang, L., W. R. Dawes, and G. R. Walker. 2001. "Response of Mean Annual Evapotranspiration to Vegetation Changes at Catchment Scale." *Water Resources Research* 37 (3): 701–8.

Zhang, Shuilei, Dawen Yang, Yuting Yang, Shilong Piao, Hanbo Yang, Huimin Lei, and Bojie Fu. 2018. "Excessive Afforestation and Soil Drying on China's Loess Plateau." *Journal of Geophysical Research: Biogeosciences* 123 (3): 923–35.

Zhao, Kaiguang, and Robert B. Jackson. 2014. "Biophysical Forcings of Land-Use Changes from Potential Forestry Activities in North America." *Ecological Monographs* 84 (2): 329–53.

Zheng, Heran, Yunqi Wang, Yang Chen, and Tingyang Zhao. 2016. "Effects of Large-Scale Afforestation Project on the Ecosystem Water Balance in Humid Areas: An Example for Southern China." *Ecological Engineering* 89 (April): 103–8.

Zhou, Guoyi, Xiaohua Wei, Yan Luo, Mingfang Zhang, Yuelin Li, Yuna Qiao, Haigui Liu, and Chunlin Wang. 2010. "Forest Recovery and River Discharge at the Regional Scale of Guangdong Province, China." *Water Resources Research* 46 (9). https://doi.org/10.1029/2009wr008829.

Zurba, Melanie, Karen Beazley, Emilie English, and Johanna Buchmann-Duck. 2019. "Indigenous Protected and Conserved Areas (IPCAs), Aichi Target 11 and Canada's Pathway to Target 1: Focusing Conservation on Reconciliation." *Land*. https://doi.org/10.3390/land8010010.