CHAPTER 6

Mitigation measures in land systems

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Chapter 6 Contents

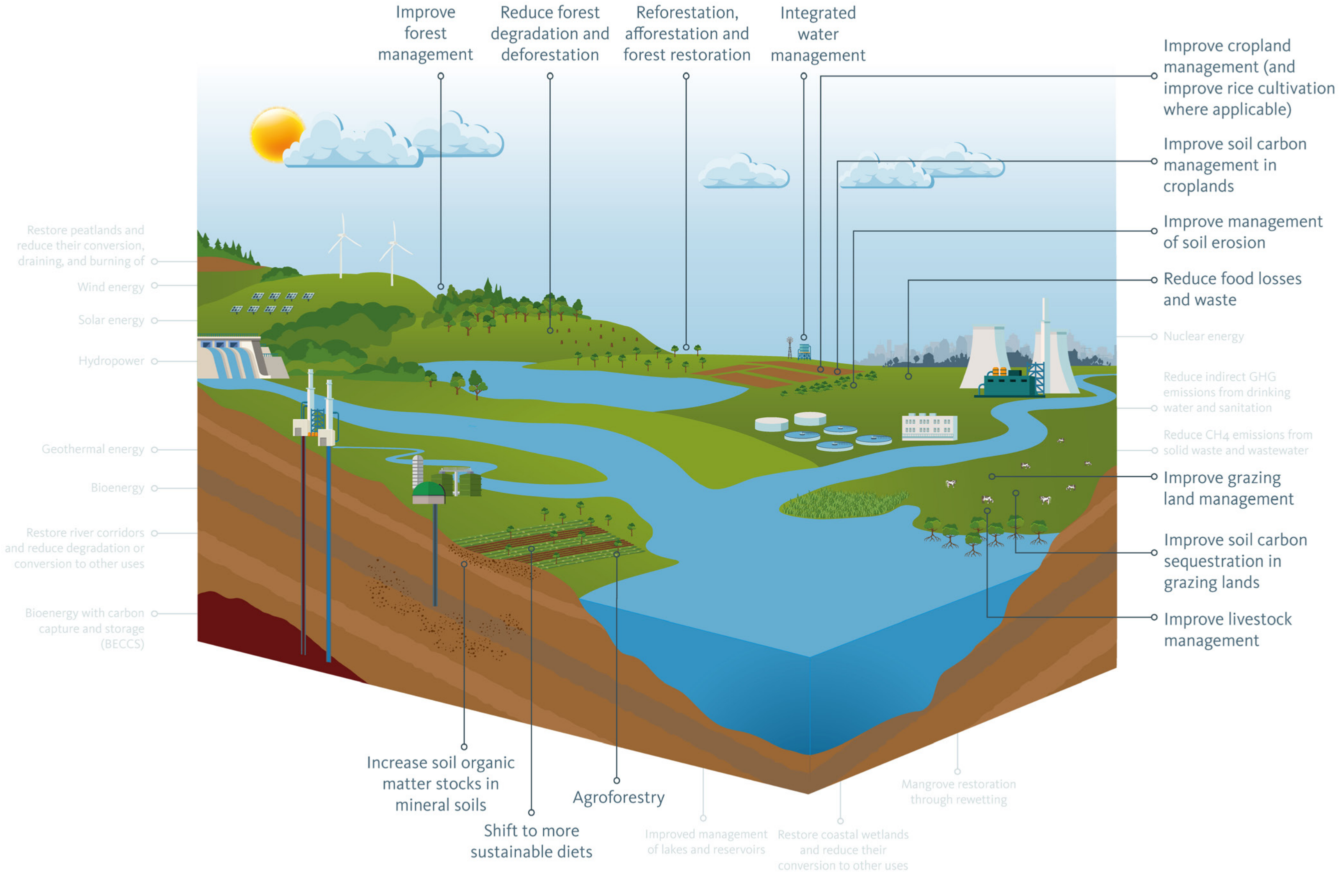


Figure 6.0. Mitigation measures in land systems. Source: SIWI.

Highlights

- Climate mitigation measures in land systems are an important means of protecting existing carbon sinks and binding carbon to soil, and to below- and above-ground biomass, in land-based ecosystems. The success of climate mitigation in land systems depends substantially on water availability and dynamics, which are prone to unpredictable and unfavourable variations under current and future environmental changes.
- Climate change has already altered water cycles in many land systems to a significant extent and the strength of the carbon sink effect appears to be declining in some terrestrial ecosystems, including some tropical forests.
- Halting deforestation and forest degradation in major forest biomes helps to preserve favourable water cycle dynamics at the continental, 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 converting forest carbon sinks into carbon sources.
- Mitigation in natural grasslands, pastures, and croplands depends primarily on improved water management. This includes reducing soil erosion by water by adopting agroecological methods such as agroforestry, which can protect and improve below- and above-ground carbon stocks.
- Mitigation measures in land systems can have notable synergies and trade-offs with local- to regional-level water sustainability goals. Conservation, restoration, and sustainable land and forest management have the potential to decrease flood risk, increase groundwater recharge, and increase water vapour exchange with the atmosphere, thereby enhancing local cooling and boosting regional rainfall. However, misguided implementation of mitigation measures can cause local water shortages, biodiversity loss, and harm to local communities.

6.1 Introduction

Climate mitigation in land systems can be focused on three main actions: i) reduce emissions from agriculture, forestry, and other land-use systems; ii) enhance the capacity of ecosystems and agroecosystems to sequester carbon; and iii) protect existing greenhouse gas (GHG) sinks in such ecosystems as forests, wetlands, peatlands, and soils. The Intergovernmental Panel on Climate Change (IPCC 2022) estimates that land systems could provide 20 to 30 per cent of the mitigation required to ensure global warming stays at less than 1.5°C above pre-industrial levels.

The mitigation potential of land systems is connected intimately with and depends on the water cycle. Healthy ecosystems and sustainably managed land systems rely on stable access to freshwater and reliable weather cycles. However, many of the world's forests, grasslands, and agricultural systems are in poor condition and suffer from unsustainable management, leading to disturbed water cycles, biodiversity loss, and land degradation, which also exacerbate climate change. Interactions between the impacts of climate change and land degradation can influence the capacity of soil to store carbon and act as a carbon sink. Thus, measures to reduce land degradation also have positive impacts on climate mitigation (Figure 6.1.).

At the same time, climate change can exacerbate many degradation processes and introduce new ones (such as thawing of permafrost or biome shifts); this is an important consideration in climate mitigation strategies (IPCC 2019). In croplands, increased decomposition usually leads to reduced soil organic carbon, which also negatively affects soil productivity and carbon sinks. In tropical forests, a drier hydroclimate and deforestation are causing reductions in net carbon uptake.

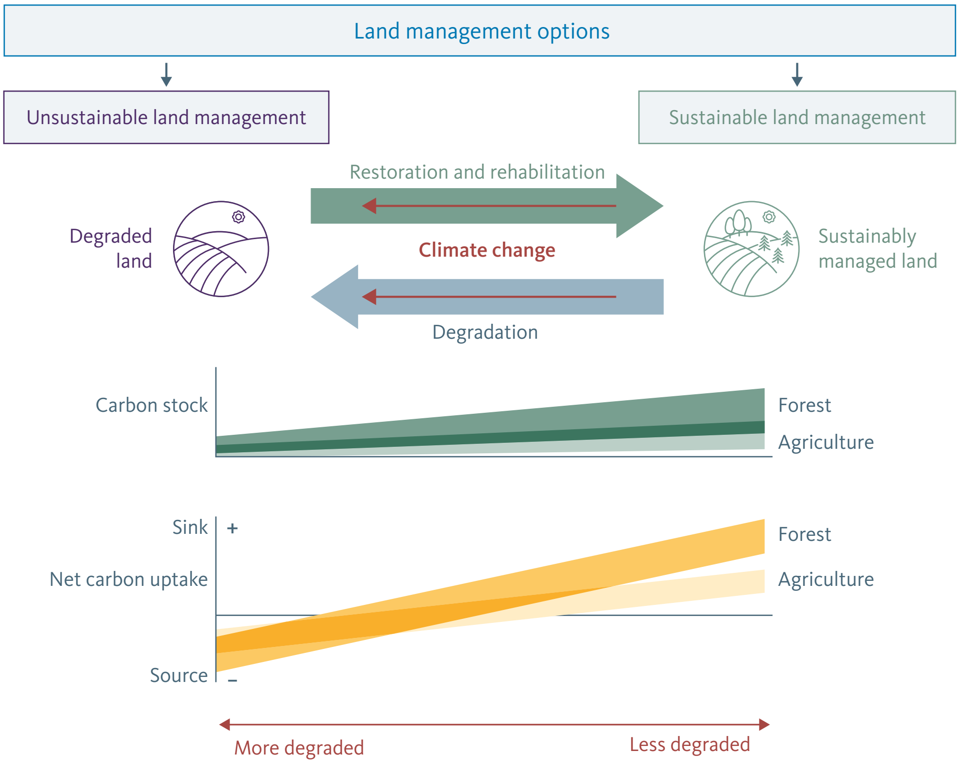


Figure 6.1. Conceptual illustration of interactions between the impacts of climate change and land-use management, and how these influence the capacity of soil to store carbon and act as a carbon sink. Source: IPCC (2019).

In addition, agriculture, forestry and other land use (AFOLU) is the only sector in which mitigation via large-scale carbon dioxide (CO_2) removal (e.g., through afforestation/reforestation or soil organic carbon management) may be possible currently and in the short term (IPCC 2022). Such 'negative emissions' (i.e., net CO_2 removal) from ecosystems are part of all IPCC scenarios that limit global warming to 1.5°C (Masson-Delmotte et al. 2022). Over 90 per cent of AFOLU emissions result from agricultural practices, with an estimated mitigation potential of 4.1 gigatons of CO_2 equivalent ($GtCO_2$-e) per year through measures taken across the sector over the next three decades (IPCC 2022). Given its considerable potential, land-based mitigation can and should be an essential component of Nationally Determined Contributions (NDCs) under the Paris Agreement (see Box 6.7 in section 6.6.1.).

There is strong evidence that climate mitigation in land systems can be effective from a biophysical and ecological perspective. However, to date, the AFOLU sector globally has contributed only modestly to net reductions (about 0.65 $GtCO_2$ per year of reduction from 2010 to 2019, or 1.4 per cent of global emissions). This is due mainly to governance challenges relating to a 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), and other adverse social impacts associated with land rights, and blue and green water availability, for example. Over 70 per cent of freshwater withdrawals are used for irrigation in agriculture and, by 2050, an estimated 15 per cent increase in water withdrawals is expected (Khokhar 2017). At the same time, about 80 per cent of the world's cropland is entirely rainfed. Land management measures here are particularly susceptible to the impacts of drought induced by climate change. Globally, over 80 per cent of all drought impacts occur in the agricultural sector. There is therefore a need to plan for and implement land management measures that can contribute to both mitigation and adaptation to climate change using integrated approaches that have the potential to synergistically address today's multiple environmental challenges while also improving governance structures (IPCC 2019; Pörtner et al. 2021; also see Chapter 9).

Improved cropland management, conservation and restoration of soils, and restoration of degraded land for climate mitigation may lead to enhanced resilience. There are also 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 between farmers and pastoralists where pastoralists' access to grazing lands becomes reduced (Behnke 2018).

In this chapter, we examine the potential and water-related risks of land system climate mitigation measures (section 6.2), focusing on forests, grasslands, pastures, and croplands. Sections 6.3 and 6.4 map the extent of the dependence and impact on the water cycle and freshwater resources of land system climate mitigation measures. Section 6.5 addresses the 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 an outlook for the future.

6.2 Mitigation potential in land systems

The selection of mitigation measures addressed in this chapter is based on: i) the estimated mitigation potential following the categories of IPCC (2019) (see Table 6.1); and ii) the level of impact on or demand for freshwater. Based on these criteria, the chapter focuses on the following measures: reforestation/afforestation and forest restoration; reduced deforestation and forest degradation; improved forest management; improved carbon management and soil carbon sequestration in croplands, agroforestry, and grasslands; and reduced methane emissions through improved rice cultivation. In this context, it is also important to highlight mitigation measures linked to dietary shifts and reductions in food loss and waste. These measures hold high potential to mitigate climate change but have a low direct impact on or demand for freshwater. The issues of dietary shifts and food loss and waste are addressed further in Chapter 8.

Land-based ecosystems absorbed around 30 per cent 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). For instance, it has been shown that land use has a large negative impact on the potential amount of carbon that can be stored in terrestrial biomass (Erb et al. 2018) (Figure 6.2). Thus, with climate-smart management, land systems have great mitigation potential not only in natural ecosystems, but also in agricultural lands, productive forests, and other production systems. Conservation, restoration, and sustainable management of land-based ecosystems and production systems are important climate mitigation measures (see Table 6.1), while 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.

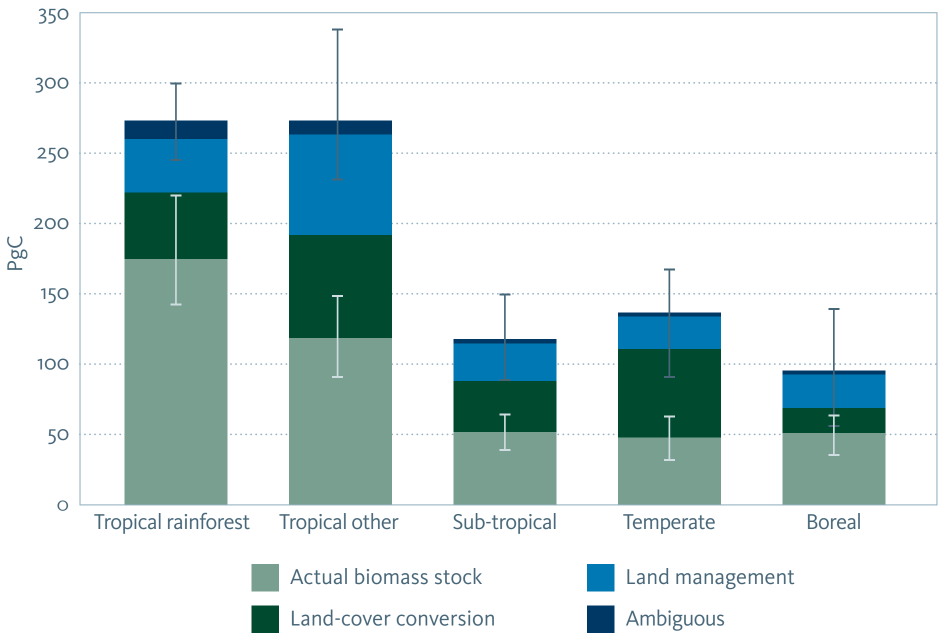


Figure 6.2. Actual biomass stocks in the world's major biomes, as well as the potential role of land-cover conversion and management to potential biomass stocks. Whiskers indicate the range of the estimates for potential (black; n=6) and actual (grey; n=7) biomass stocks. Source: Erb et al. (2018).

Table 6.1. Climate mitigation measures in land systems with high estimated mitigation potential

MITIGATION MEASURE IN LAND SYSTEMS	MITIGATION POTENTIAL $GTCO_2$-E PER YEAR 2020-2050	CONFIDENCE LEVEL
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 methane)	0.08–0.87	-
Improve water management	0.1–0.72	-

* Climate mitigation measures that have indirect impact on or demand for freshwater. Source: IPCC (2019)

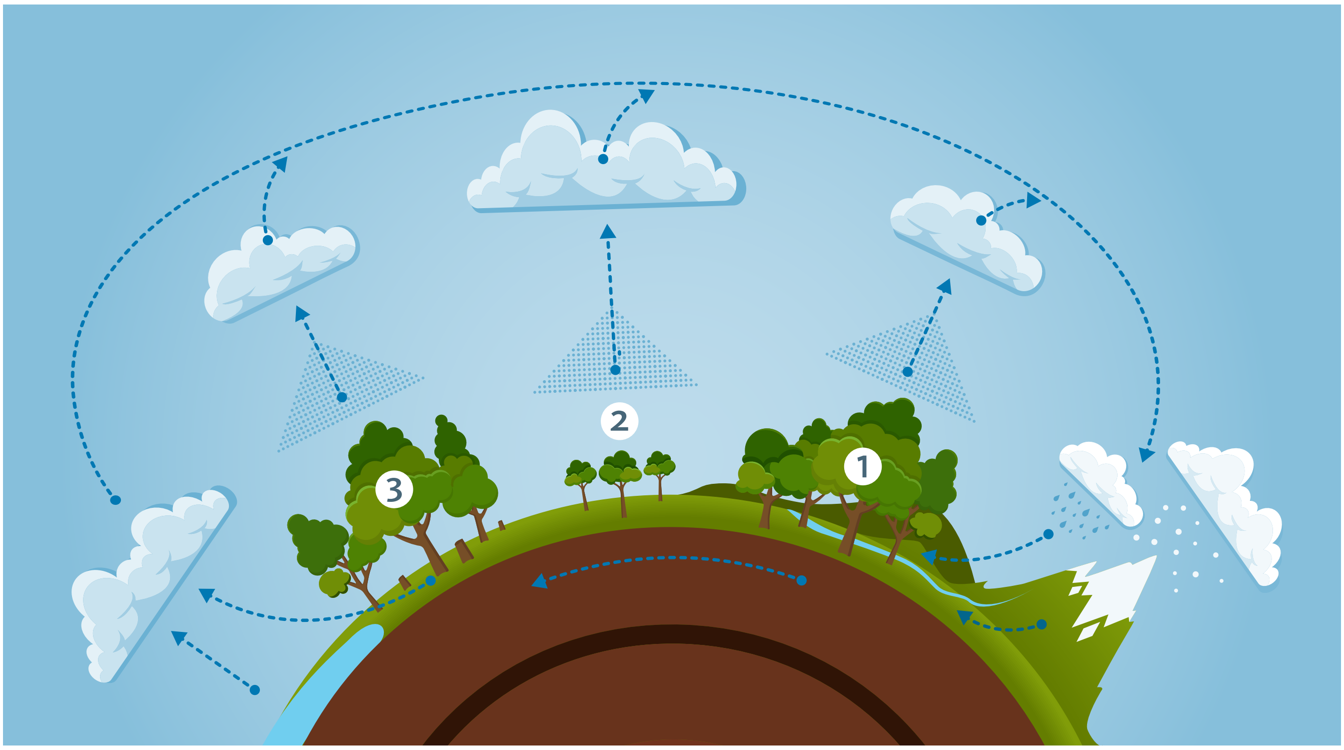
6.2.1 Mitigation potential in forests

Forests are well known to be carbon sinks, and many governments have advanced plans to plant vast numbers of trees to absorb CO_2 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, in particular, 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 6.3). Forests and trees are key elements of the water cycle and have an impact on many water cycle processes and functions, including atmospheric moisture transport, infiltration and groundwater recharge, flood moderation, fog/cloud interception, and precipitation recycling at regional and continental scales (Sheil et al. 2019; Ellison et al. 2017; Ilstedt et al. 2016).

Reducing deforestation and forest degradation

Reducing deforestation and forest degradation is estimated to have a mitigation potential of 1.41–7.98 $GtCO_2$-e per year over 2020–2050 (IPCC 2019). Globally, these measures also have a high potential for climate and 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 regional water cycles and climatic patterns (e.g., Luyssaert et al. 2008; 2018). Natural forests can be up to six times more effective at storing carbon than agroforestry, and up to 40 times more effective than tree plantations (per unit area 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 (Green et al. 2019; Hubau et al. 2020), as well as substantial risks for crossing deforestation tipping points beyond which self-amplifying feedback loops push the biomes towards alternative stable non-forest states (Staal et al. 2020; Zemp et al. 2017).

Tropical forests account for half of the global terrestrial vegetation carbon storage (Lewis, Edwards, and Galbraith 2015). Existing forests sequester 15.6 ± 49 $GtCO_2$-e per year, while in recent decades



① Mitigation measure 1 – Reducing deforestation and forest degradation

② Mitigation measure 2 – Reforestation, afforestation, and restoration

③ Mitigation measure 3 – Forest management

Fig. 6.3. Conceptual overview of forest systems mitigation measures and their impacts on the water cycle. Source: SIWI.

under elevated atmospheric CO_2 concentration, deforestation and forest degradation emitted 8.1 ± 2.5 $GtCO_2$-e per year (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 African rainforests), due primarily to negative drought and temperature impacts on tree growth and mortality (Hubau et al. 2020) (Figure 6.4). Due to a combination of forest area loss, falling carbon sink strength per forest unit area, and rising anthropogenic carbon emissions, the fraction of anthropogenic CO_2 emissions removed by tropical forests has fallen from 17 per cent in the 1990s to just 6 per cent in the 2010s (Hubau et al. 2020). The carbon sink strength will continue to decline, with the magnitude depending to some extent 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 and human-induced fire disturbance, protect the forest water cycle, and enact a rapid halt to anthropogenic GHG emissions. The altitude of the forest may also have an impact on the carbon storage capacity. Recent findings show that the carbon sink strength of Andean rainforests is higher for lowland than for highland rainforests (Duque et al. 2021); while montane forest sites in Africa could 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 CO_2 fertilization (Walker et al. 2021). However, this trend appears to have recently slowed due to a weakening temperature control of spring carbon uptake (Piao et al. 2018) and a declining CO_2 fertilization effect on vegetation photosynthesis (Wang et al. 2020).

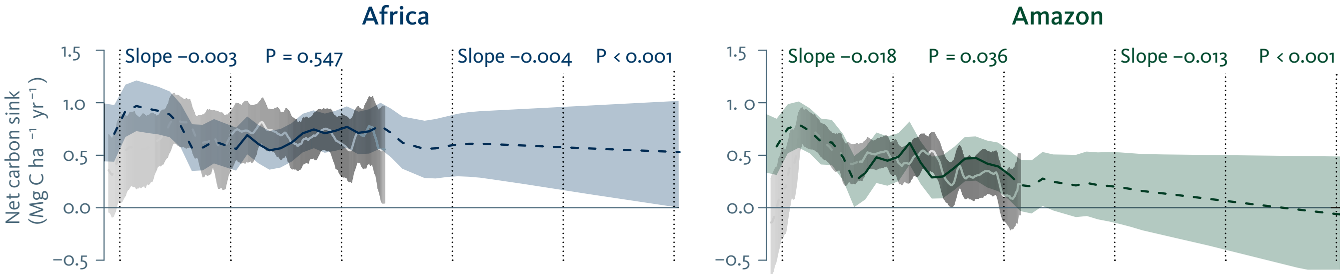


Figure 6.4. The net carbon sink - i.e., the ability of the forest to absorb more carbon than it releases - has already peaked in both the African and the Amazonian forest and is projected to continue to decline. Source: Hubau et al. (2020).

Reforestation, afforestation, and forest restoration

These are the mitigation measures estimated to have the highest climate mitigation potential globally (up to >10 $GtCO_2$-e per year 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, contributing to a reduction in both flood and drought risk (Teo et al. 2022). Under unfavourable conditions, increased tree cover can be associated with negative impacts on streamflow, 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 (including irrigation demand) and with a substantial risk of disruption 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 has recently 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 through natural regeneration, plantation, or direct seeding; and they can have different purposes, such as timber and pulp production or ensuring the provision of a high quality and quantity of water to an urban area (Zhang et al. 2020). Forest restoration can accelerate the recovery of degraded forests, with special focus on reinstating ecological processes, recovering the forest structure, and restoring the biodiversity typical of climax forests (Elliott, Blakesley, and Hardwick 2013). However, the mitigation benefits of forest restoration depend 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 (Lal et al. 2018), and indirectly through increasing evapotranspiration, which reduces local air temperatures (Zhang et al. 2020) and drives moisture recycling that results in rainfall generation benefits (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 (Bárcena et al. 2014; Paul et al. 2002). All three of the above-mentioned measures should complement, not substitute, measures to reduce deforestation and prevent forest degradation (Di Sacco et al. 2021), since the carbon stocks, biodiversity, and other ecosystem services provided by old-growth forests cannot be provided by newly planted forests within relevant societal and climate change timescales. 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 countries, particularly in Africa (Busch et al. 2019). Also, (assisted) natural regeneration approaches are more cost-effective than planting (Crouzeilles et al. 2020).

The tropics have the largest forestation potential 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 has been 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 for forests than for lower-growing vegetation (Zhao and Jackson 2014), which can cause substantial surface warming, cancelling the potential carbon sequestration benefits (Arora and Montenegro 2011; Betts 2000; Schaeffer et al. 2006; Sonntag et al. 2016).

Hotspot areas for forest restoration are found primarily in Brazil, Colombia, India, Indonesia, and Madagascar (Brancalion et al. 2019). Hotspot regions for afforestation (as well as reforestation) include China, South America, sub-Saharan Africa, and the United States of America (USA), with South America and sub-Saharan Africa being responsible for at least 50 per cent of the climate change mitigation potential from afforestation (Doelman et al. 2020). A recent controversial study estimates that globally up to 0.9 billion hectares (ha) of land are available for tree canopy cover, representing a total carbon storage potential of up to 205 gigatons of carbon (GtC) (range: 133–276 GtC) over decadal timescales (Bastin et al. 2019). The potential would be higher if forestation enhancement of the water cycle is considered, but the actual land areas that can be considered for forestation are substantially lower if social, legal, ethical, and political factors are accounted for (Arora and Montenegro 2011; Betts 2000; Grainger et al. 2019; Lewis et al. 2019; Schaeffer et al. 2006; Skidmore et al. 2019; Veldman et al. 2019). Increased droughts and wildfires occurring as a result of severe climate change (RCP8.5[1]) may considerably decrease the potential canopy cover (by 0.223 billion ha and 46 GtC by 2050), particularly in the tropics (Bastin et al. 2019).

The realised mitigation effect from reforestation measures can also 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 (Sloan et al. 2018; Veldman et al. 2017; Wilkinson et al. 2018) (also see Chapter 5). Further, forestation and tree planting should not be considered as a silver bullet solution to climate and biodiversity crises without taking bold steps to reduce GHG emissions (Holl and Brancalion 2020) and without considering the social and environmental justice dimensions, where over 294 million people in the global South live on land considered suitable for tropical forest restoration (Elias et al. 2022; Erbaugh et al. 2020; Fleischman et al. 2022).

Sustainable forest management

This has the potential to mitigate 0.4–2.1 $GtCO_2$-e per year (IPCC 2019). Forest management measures such as selection of tree species, fertilization, thinning, irrigation, or prescribed burning (Laclau et al. 2005; Ontl et al. 2019; Stape et al. 2010) can be critical for increasing carbon uptake and ensuring win-wins for both preventive and active forest mitigation measures. On the other hand, unsustainable forest management risks causing land degradation, reducing carbon stocks of forest land, and increasing GHG emissions, which can also lead to negative impacts on water quantity, quality, and flows.

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 (Bastin et al. 2019; Seidl et al. 2017). The effectiveness of forest management mitigation measures is highly site specific and depends on local knowledge to make informed decisions on species selection and planting or harvesting strategies, for example. Harvesting natural old-growth forests that have not previously been logged inevitably leads to increased emissions. On deforested land, however, reforestation interventions leading to sustainable forestry can increase both carbon storage and biodiversity.

The temporal aspects relating to forest management initiatives are 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 and logging intensity (Lundmark et al. 2018; Mackey et al. 2020), 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 dependency on products with high negative impact on climate change, such as fossil-fuel-based materials and energy. The trade-off between maximizing forest carbon stocks and maximizing substitution depends on many factors, including the state of the managed

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[1] RCP8.5 is a pathway where GHG emissions continue to grow unmitigated, leading to a best estimate global average temperature rise of 4.3°C by 2100.

forest, regrowth rates, and estimated emissions from the product or energy source that is substituted. In a long-term 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).

Sustainable forest management is a globally recognized concept that can have multiple objectives, including enhanced water quantity, quality, and flows; timber production; biodiversity; and carbon sequestration and storage. Within sustainable forest management, efforts are focused on society's various needs, including water security. It 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 carbon stocks in boreal and temperate forest areas have increased slightly (by around 6 per cent) following forest area expansion due to reforestation of agricultural land and reduced harvesting in young secondary forests, while soil carbon stocks in tropical forests have declined slightly (by around 7.5 per cent) due to deforestation (Scharlemann et al. 2014). However, the mitigation potential achieved by protecting and enhancing forest soil carbon stocks is quite small (9 per cent) compared to, for example, soil carbon stored in grasslands and agriculture (47 per cent) (Bossio et al. 2020).

6.2.2 Mitigation potential in natural grasslands, pastures, and croplands

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 or sink function of ecosystems, and degraded lands cause increased GHG emissions, with potential feedback effects on the global climate system. In addition, combinations of global change drivers such as elevated atmospheric CO_2 concentration, warming, fertilization, grazing, and land-use change influence the carbon sequestration of natural grasslands, pastures,

Sunrise over forested peaks of western Thailand. Source: Shutterstock.

and croplands. The water cycle is of high importance for carbon sequestration and storage in soils, while both land use and climate change may threaten this function.

The mitigation potential of agricultural systems is estimated at 4.1 (1.7–6.7) $GtCO_2$-e per year (IPCC 2022). Important mitigation measures include improved cropland and grassland soil carbon management, agroforestry, and improved rice cultivation. In these ecosystems, the sequestration rates depend on soil depth, initial soil carbon content, and the period of management practices. A review of arable land shows that sustainable land management can increase soil carbon sequestration, especially when using novel methods such as soil amendments (e.g., compost) and shifting to perennial grain crops, which can reduce losses and increase inputs of carbon through their roots (Olsson et al. 2023). Soil carbon sequestration will be especially important as a short-term solution to mitigating climate change over the next 10 to 20 years while other more effective sequestration and low-carbon technologies become viable (Minasny et al. 2017). A shift from annual to perennial crops has the greatest potential to increase soil carbon stocks to the level accumulated by the natural vegetation that preceded agriculture.

Grassland and cropland systems are highly dependent on reliable access to freshwater and an intact water cycle. In fact, agriculture accounts for 70 per cent of freshwater use worldwide, mainly for irrigation (FAO 2017). Unsustainable land use has a profound effect on the flux 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 and watershed functioning, leading to drought and reduced access to freshwater for downstream communities. In addition, agriculture is a major source of water pollution, especially from agricultural fertilizer, pesticide run-off, and discharge from livestock production (see Chapter 5).

Improved management of soils in natural grasslands, pastures, and croplands 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, run-off, and flood events on the soil; and it can reduce streamflow and sediment export by intercepting run-off and promoting water infiltration.

Improved soil carbon sequestration in natural grasslands and pastures

Grasslands, including savannas with scattered trees and open-canopy grassy woodlands, cover approximately 40 per cent of the global land surface (Dixon et al. 2014). Grassland soils store high quantities of carbon and other key nutrients, and hence are important carbon sinks in the global biogeochemical cycle (Zhou et al. 2023). Most of the biomass in grasslands is found below ground, aggregated into roots (around 700–1000 g per square metre with root lengths up to more than 2 m), where most of the carbon is stored. Consequently, grassland soils hold relatively large quantities of organic carbon and store around 28–37 per cent of the global soil organic carbon pool (Lal 2004). Despite their relatively low above-ground biomass, grasslands are thus important net sinks for atmospheric carbon, collecting nearly 0.5 GtC per year (Scurlock and Hall 1998, Imer et al 2013). The fine, extended, highly branched root system of grasses stabilizes the soil surface, significantly reducing the rate of soil weathering and degradation in exposed grasslands. Grass also accumulates organic material over a long period of time, which results in more fertile and carbon-rich soils.

Restoration of grasslands has received far less attention than that of forests and there is limited understanding of the kinds of activities that should be included in large-scale restoration of grasslands (Buisson et al. 2019). However, a recent study shows that soil carbon in tropical savannas is derived mostly from grasses (Zhou et al. 2023). 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 in the area 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 run-off and eventually improving groundwater recharge.

Improved soil carbon management in croplands

Many agricultural activities contribute to emission of GHGs, including soil drainage, ploughing, removing crop residues, adding nutrients (manures and fertilizers) and burnings. The loss of soil C is accentuated by unsustainable management practices that cause soil degradation may further increase emissions amplifying processes such as erosion, compaction and salinization that can lead to a decline in soil quality.

Improving soil carbon management in croplands can have positive effects on climate mitigation, but more research is needed to present reliable data on the soil carbon storage potential and to enable estimation of the potential of this measure for mitigation. Still, measures to keep a continuous vegetation cover and thus increase the soil carbon stock require sufficient 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 et al. 1994; Li et al. 2019). Soil and water conservation practices aimed at reducing water erosion and surface run-off, mitigating the impacts of floods, and improving soil infiltrability are crucial components in successful restoration of degraded soil. Sustainable soil and land management practices, including agroforestry and conservation agriculture, can improve capacity for soil infiltration, resulting in reduced surface run-off 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 to the protection of soil organic carbon stocks, and thus serve as important tools for mitigating climate change (Amundson and Biardeau 2018). A recent study predicts that conservation agriculture can reduce global potential soil erosion rates by around 5 per cent between 2015 and 2070 (Borrelli et al. 2020; see Figure 6.5). The study also indicates a global trend where a more intense hydrological cycle due to increased temperatures may increase soil erosion.

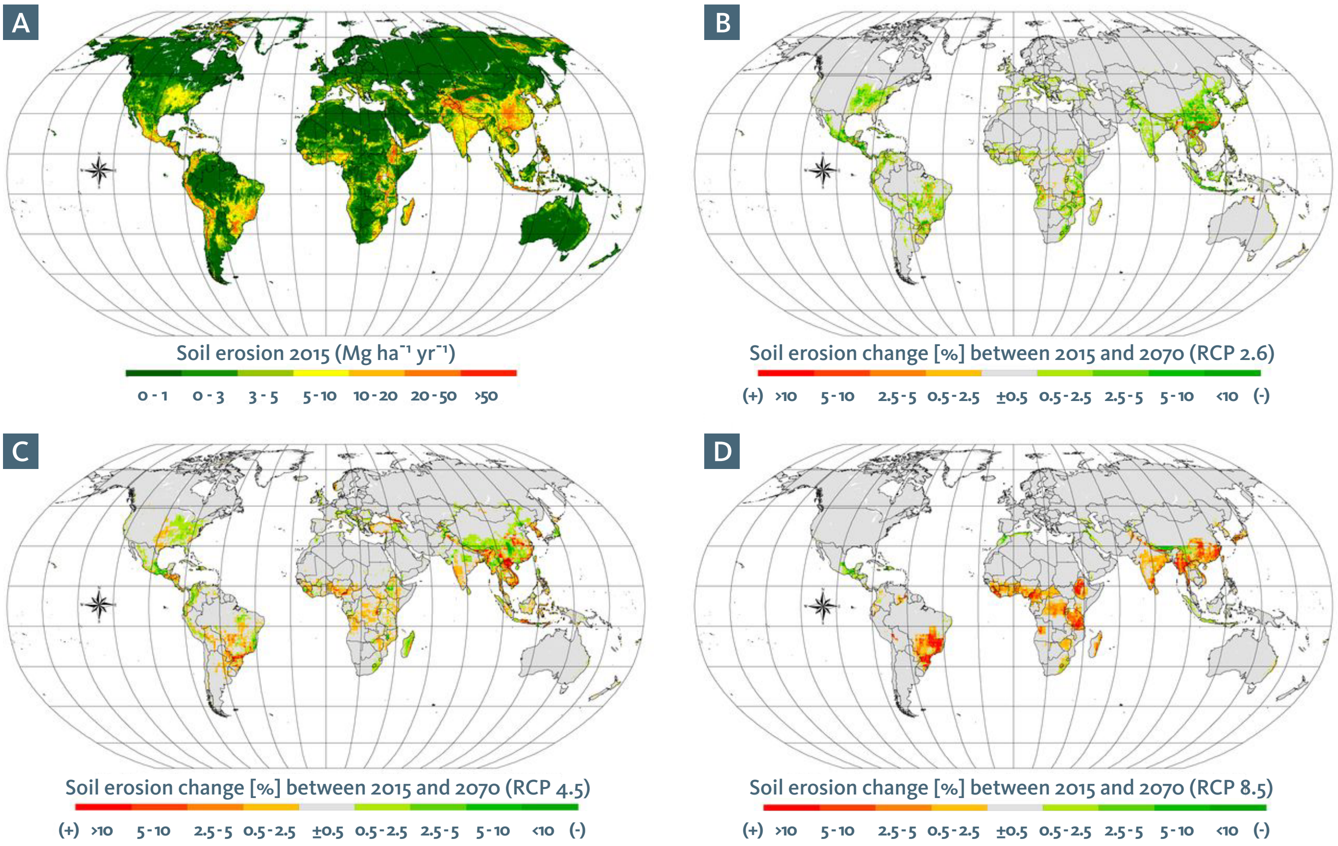

Figure 6.5. Predictions of annual average erosion rates between 2015 and 2070 by modelling change in potential global soil erosion by water using three alternative scenarios (2.6, 4.5, and 8.5) known as 'shared socioeconomic pathway and representative concentration pathway (SSP-RCP)'. The scenarios suggest different impacts on soil erosion by 2070: A. Soil erosion in 2015; B. 10 per cent soil erosion decrease by 2070 (2.6); C. 2 per cent soil erosion increase by 2070 (4.5); D. 10 per cent soil erosion increase by 2070 (8.5). Source: Borrelli et al. (2020).

Agroforestry

Trees in agricultural land positively influence the capacity of the soil to absorb, store, and release water through enhanced litter inputs and the activity of roots and soil fauna (Bargués-Tobella et al. 2020; Benegas et al. 2014). The integration of trees with agriculture 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 providing multiple social and ecological co-benefits (IPCC 2019), such as enhanced biodiversity, crop production, and food and nutrition security.

Agroforestry practices can transform degraded or less productive agricultural land and support the hydrological cycle by regulating the water supply, 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 promoting 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 (Laestadius et al. 2011). The main focus of FLR is to regain ecological functionality while also enhancing human well-being across deforested or degraded forest landscapes. Compared with other restoration practices included in FLR, agroforestry is particularly effective in restoring biodiversity and ecosystems while also delivering food and income security (FAO 2022).

The Great Green Wall initiative is an example of a large-scale restoration initiative that involves vast areas of cropland, rangeland, grassland, and savanna in the Sahel and Sahara region, where severe droughts occur and soil and land degradation are common. The initiative includes water and soil conservation measures to increase climate change resilience. 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 summarizes the experiences and practices introduced.

Box 6.2. The Sahara and Sahel Great Green Wall initiative

The Great Green Wall initiative is a Pan-African programme launched in 2007 by the African Union. 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. Reducing and reversing land degradation is important for climate change mitigation as well as for achieving the Sustainable Development Goals (SDGs), including the targets relating to food and water security (SDGs 2 and 6), and life on land (SDG 15), and to balance the losses and gains of productive land to achieve land degradation neutrality (Cowie et al. 2018).

Figure 6.6 . The Great Green Wall initiative original 11 member countries. Source: UNCCD (2020).

Starting with 11 core countries (Figure 6.6), the initiative has now expanded to include the drylands of North and South Africa and represents a total restoration potential of over 600 million ha (UNCCD, 2020). The European Union (EU), Global Environment Facility (GEF) and World Bank, among others, have provided financing for a number of implementation projects. These include the Sahel and West Africa Programme in Support of the Great Green Wall Initiative, and the Building Resilience through Innovation, Communication, and Knowledge Services project (Goffner et al. 2019; UNCCD 2020). So far, the initiative has worked with other related national and international projects to comprise an estimated total carbon sequestration potential of 138 megatons of carbon (MtC) (UNCCD 2020).

The Great Green Wall initiative has moved beyond its original conception as a wall of trees into a mosaic of sustainable land management 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 sustainable land management measures are most appropriate for each location. For example, the most common practices in Burkina Faso, Mali, and Niger are soil and water conservation measures, sand dune stabilization, and soil fertility improvement, while in Mauritania, water harvesting and sand dune stabilization techniques are the most important (Chirwa and Larwanou, 2017).

Moreover, water is at the centre of restoration in drylands as interventions aiming to increase 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 streamflow 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 higher evapotranspiration from trees, while the opposite happens with deforestation (e.g., Bosch and Hewlett 1982; Farley et al. 2005). 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 maximized with an intermediate tree cover (Ilstedt et al. 2016). Sites treated with Zaï and half-moons (farming techniques of digging pits in less permeable soil for water harvesting) in Niger exhibited high soil water storage, promoting vegetation productivity and millet yields compared to control sites, particularly in drier years (Wildemeersch et al. 2015). Soil and water conservation practices in Burkina Faso such as stone bunds, gullies, and permeable dams have contributed to the regeneration of trees and shrubs with further carbon sequestration (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 the following (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, grasslands, and croplands.
- 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.
- Mobilizing 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 enable the flourishing of green economies and enterprises.

The most common sustainable land management techniques adopted under the initiative were forest and watershed management, terracing and soil measures, and assisted natural regeneration and reforestation (Table 6.2). Other common activities that often covered smaller areas were multipurpose gardens, nurseries, and fire and wind breaks (UNCCD 2020). Through the adoption of these measures, the initiative has so far contributed directly to the restoration of 4 million ha of degraded lands and created momentum for other national and international projects with restoration of an additional 17.8 million ha in the original core countries in the Sahel. This totals an estimated carbon sequestration potential of 138 MtC (UNCCD 2020). Value chains have been created including honey, Arabic gum, baobab, and fodder, which have also contributed to the creation of 335,000 jobs (UNCCD 2020).

Table 6.2. Great Green Wall sustainable land management practices and their benefits

	Production	**Landitation**	**Plant protection**	**Erosion control**	**Water harvesting and retention**
Forest management and agroforestry	FMNR Multi-purpose gardens 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

Note: FMNR = farmer-managed natural regeneration. Source: Chirwa and Larwanou (2017); Maisharou et al. (2015).

However, progress among countries has not been uniform, with some showing more achievements than others (UNCCD 2020). Mirzabaev et al. (2021) evaluated the economic costs and benefits of land restoration under the initiative. 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 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 investment needed for land restoration across the Sahel is estimated to be between USD 18 and 70 billion. To increase the speed and scale of the interventions, a renewed financial commitment took place at the One Planet Summit in January 2021 leading to a pledge of over USD 19 billion by several multilateral and bilateral organizations as well as the creation of the Green Wall Accelerator to facilitate the coordination of donors and stakeholders (UNCCD 2021).

Among the many programmes in place to support the Great Green Wall initiative, GEF is funding projects to further enhance collaboration between the various countries and stakeholders. The goal is to create an enabling environment for scaling up sustainable land management interventions and policies as well as to support the mobilization of funds, and to integrate and harmonize different scientific tools and methods and 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 Sustainable Land Management in the Great Green Wall Initiative Countries takes stock of previous GEF sustainable land management projects in the four pilot countries of Burkina Faso, Ethiopia, Niger, and Senegal (Figure 6.7). The ongoing analysis of these projects will provide an indicator framework for the monitoring of socio-economic impacts (O'Byrne et al. 2022), a scaling evaluation framework to inform future investments in the region (Mechiche-Alami et al. 2022), and the identification of land degradation hotspots and an impact assessment of interventions. The goal is to maximize the environmental and socio-economic benefits of sustainable land management investments, such as carbon sequestration and regulation of water, and thereby to contribute to food and water security in the Sahel. Through a combination of partners,* including remote sensing companies, international organizations, and research institutes, this project develops science-based assessments and provides training to technical staff in the initiative's country offices.

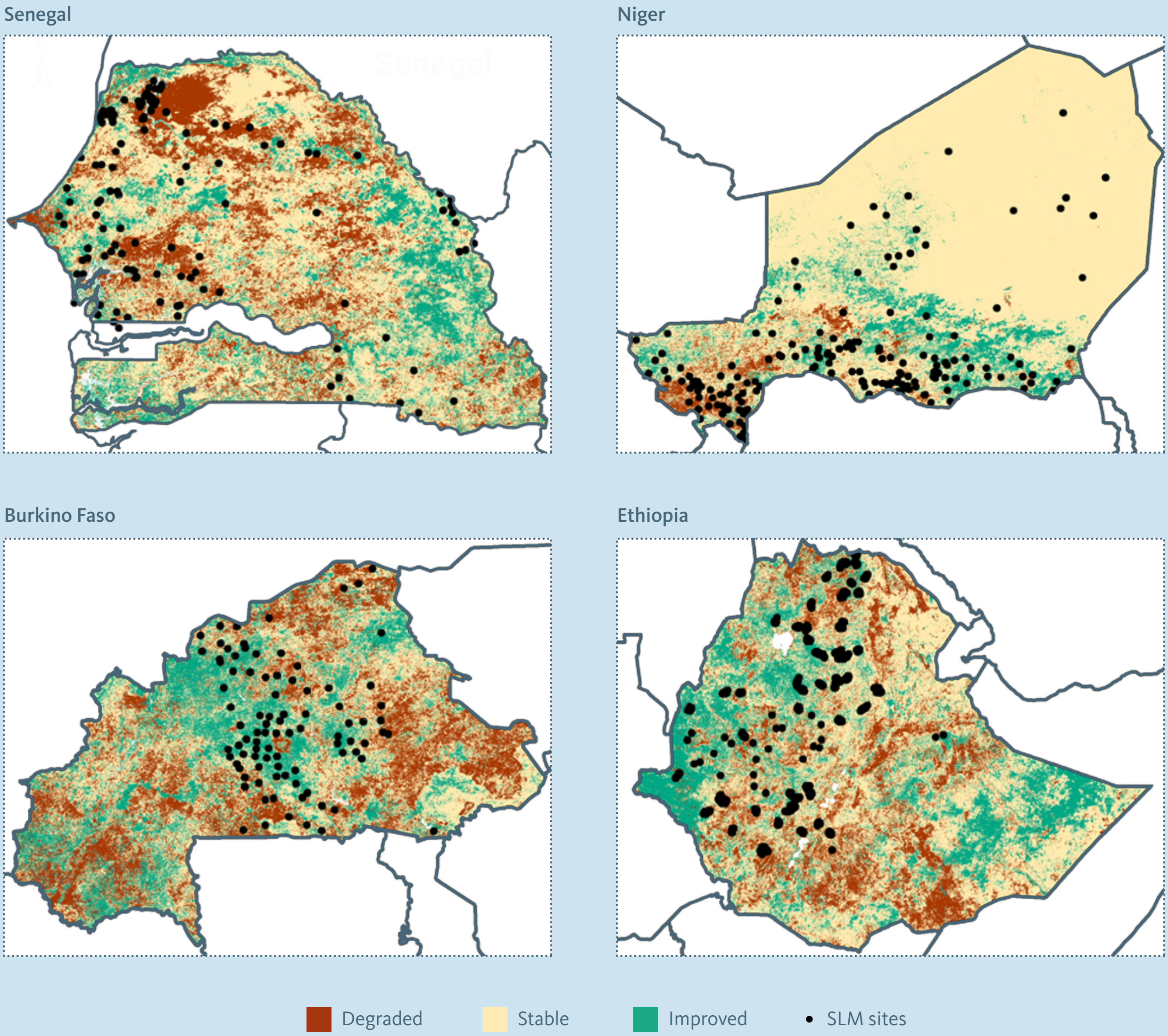

Figure 6.7. Sustainable land management intervention sites under GEF projects and assessment of land degradation between 2001 and 2018 in Burkina Faso, Ethiopia, Niger, and Senegal. Source: trends.earth (http://docs.trends.earth/en/latest/).

* The partners include Agrhymet, Danish Hydraulic Institute, European Space Agency, Lund University Centre for Sustainability Studies, National Aeronautics and Space Administration, Sahara and Sahel Observatory, Sistema, and United Nations Environment Programme.

Improved rice cultivation

Rice is a staple food for more than 50 per cent of the world's population. Rice paddies are the largest artificial type of wetland occurring globally and so constitute an important source of GHG emissions (IPCC 2022). The global mitigation potential from improved rice cultivation has been estimated to cover a range from 0.08 to 0.87 $GtCO_2$-e per year between 2020 and 2050 (IPCC 2019). 90 per cent of emissions in rice cultivation are associated with methane emissions from anaerobic conditions. When farmers adopt continuous flooding, application of nitrogen fertilizer, and use of machinery there are higher GHG emissions than with more traditional methods of production. Puddling and continuous submergence of rice fields facilitates the activity of methanogenic bacteria, thereby increasing methane emissions (Pathak et al. 2013). In contrast, the aerobic conditions of rice paddies that are periodically dry have lower methane emissions and thus may reduce global warming (Basavalingaiah et al. 2020).

The main mitigation potential in rice cultivation 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., through alternate wetting and drying (Adhya et al. 2014). In addition, compared with transplanted rice production systems, direct-seeded rice can significantly reduce GHG emissions and contribute to water saving, since less water is required for nursery preparation and puddling. The method is also less energy and labour intensive (Pathak et al. 2011). Other factors contributing to GHG emissions stem from fertilizer application and energy used for water pumping. Another important mitigation measure is to introduce improved rice varieties that are drought resistant or more suitable for rainfed cultivation (Africa has led the way in developing such cultivars).

Globally, the area under rice cultivation has grown by 11 per cent between 1990 and 2019 (FAO 2021) and now occupies more than 160 million hectares, of which Asia covers about 88 per cent (Chakraborty et al. 2017). About 90 per cent of rice is produced and consumed in Asia, but cultivation is rising in other regions including sub-Saharan Africa (Carlson et al. 2016; IPCC 2019). The demand for rice is growing, and global rice production is projected to increase by 13 per cent from 2018 to 2028, with the largest increases occurring in Africa and Asia (OECD/FAO 2019). However, some projections of GHG emissions from rice cultivation are showing a slight decline by 2030. This may be explained in diets shifting to include more protein as the average per capita income increases.

Box 6.3. Improved rice cultivation in India

In India, 85 per cent of the population relies on rice as the staple food. The area under rice has increased from 30.8 to 43.8 million ha from 1950 to 2021, with an increase in production volume from 20.6 to 122.3 million tons (Government of India, 2021). Productivity increased from 668 to 2,400 kg per ha during the same period (Dey and Dinesh 2020). The eastern part of the country, including Assam, Bihar, West Bengal, Eastern Madhya Pradesh, Eastern Uttar Pradesh, and Odisha, is an important area for rice cultivation, accounting for about 63.3 per cent of India’s total area under rice cultivation. India is a net exporter of rice, exporting about 20 per cent of the yearly produce. Iran, Iraq, Saudi Arabia, the United Arab Emirates, and Yemen are major importers of basmati rice, while Benin, Cote d'Ivoire, Nepal, Senegal, and Togo are major importers of non-basmati rice from India.

Rice production systems and the extent of methane emissions

In India, rice production systems are classified based on soil water conditions and categorized into the following four broad groups (Rao et al. 2017, Meera et al. 2014). Values for methane emissions from these production systems are presented in Table 6.3.

- **Irrigated rice ecosystems:** These are grown in bunded fields with irrigation on one or more crop rotations per year. Usually, farmers try to maintain 5–10 cm of water in the field. The wet season (June to October) is the main season for rice cultivation (Rao et al. 2008). An area of about 22 million ha is under irrigated rice systems, representing around 49.5 per cent of the total rice area.

- **Rainfed upland rice ecosystems:** The area under cultivation is about 6 million ha, accounting for 13.5 per cent of the total rice area. The monsoon season (June to September) is the main season for rice cultivation. Rice is mostly direct sown and in the dry season the fields are generally dry and bare.
- **Rainfed lowland rice ecosystems:** Here, rice is grown in bunded fields that are flooded with rainwater for at least part of the cropping season to a depth of more than 100 cm for no more than 10 days. This system accounts for 32.4 per cent of the total area under rice cultivation. Farmers have little control on water, and water depths can be shallow (up to 25 cm), medium-deep (up to 50 cm), or deep (up to 2 m). Medium- to long-duration cultivars are grown, depending on the water depth. There may be a water shortage during crop establishment and excess water during the later stages of growth. Cultivars grown should therefore have tolerance to drought in the initial stages and to submergence at later stages as well as elongation ability in semi-deep or deep water.
- **Flood-prone rice ecosystems:** These are prevalent where farmers face temporary submergence of 1–10 days or long periods of submergence of 1–5 months in depths from 50 to 400 cm or more. This system is also adopted where daily tidal fluctuations cause complete submergence (Mohanty et al. 2013). They account for about 4.6 per cent of the total rice-growing area. Yields are very low (1.5 tons per ha) and variable. June to November is the main wet/flooding season. Rice varieties are selected according to their level of tolerance to submergence.

Table 6.3. Methane emissions from different rice production systems in India (2007)

Ecosystem	**Water regime**	**Rice area (million ha)**	**Methane emission (million tons)**
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**

Source: Bhatia et al. (2013)

Reducing emissions through improved water management

Improved water management practices in rice cultivation create aerobic conditions; these control the activity of soil microorganisms resulting in a reduction in methane emissions. The choice of irrigation method affects the soil moisture and can regulate the release of GHGs. Common irrigation methods in rice cultivation include alternate wetting and drying (AWD), mid-season drainage and intermittent irrigation, intermittent flooding, and intermittent drainage, all of which may affect the soil oxidation potential. AWD can reduce methane production substantially because the time intervals between dry and wet conditions enable a shift from aerobic to anaerobic soil conditions. It can also improve water-use efficiency. These irrigation methods facilitate soil oxidation by boosting root activity and soil oxygen-bearing capacity, while minimizing the input of water that creates anaerobic conditions. Methane emissions can be reduced by 15–88 per cent (Mohanty et al. 2017). Intermittent drainage in rice, creating alternate anaerobic and aerobic conditions, is considered to be one of the best options for reducing methane emissions (Tyagi, Kumari, and Singh 2010).

Despite the benefits of AWD, its adoption has been limited, possible due to farmer apprehension that it may reduce yields (Carrijo, Lundy, and Linquist 2017). Deelstra et al. (2018) reported an increase in water productivity of 0.59 kg per cubic metre under AWD over conventional paddy rice (0.22 kg per cubic metre) because of water saving and better yields in two districts of Telangana in the Krishna River basin. Irrigation scheduling is one method that can adjust water use, time, and place of application for optimized crop production, while reducing total water use and improving the performance of irrigation systems. Scheduling irrigation with low-cost tensiometers can be a technical support to optimize irrigation in rice, resulting in water saving of about 13 per cent (Vatta et al. 2018).

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

Micro-irrigation can increase water-use efficiency and improve crop yields when compared with flood irrigation methods. Various micro-irrigation methods are used in rice cultivation, such as surface drip, sub-surface drip, sprinkler, and low pressurized systems. Drip irrigation (surface and subsurface) has high irrigation efficiency in rice, providing water precisely to the crop roots. It can also minimize the energy needed for pumping water. Reduction in GHG emissions were greatest for sub-surface drip systems (36–44 per cent) followed by surface drip (17–25 per cent) in rice crops. Subsurface drip systems reduced CO_2 emissions by 17–44 per cent indicating significant mitigation potential, contributing to a yield improvement of 18–31 per cent and water saving of 23 per cent compared with the conventional method (Parthasarathi et al. 2021).

Mitigation through management of groundwater irrigation

India is the largest user of groundwater in the world and agriculture is the largest user of water in the country. Out of the total 6,881 geographical groundwater assessment units, 1,186 units (17 per cent) have been categorized as ‘over-exploited’. In addition, 313 units (5 per cent) are ‘critical’, with groundwater extraction ranging between 90 and 100 per cent of recharge (Central Government Water Board, India, 2019). The number of groundwater irrigation structures increased from 6.2 million in 1986/87 to 20.5 million in 2013/14 (Mukherji 2020). Moreover, the area irrigated by groundwater has increased greatly; from 29 per cent of the total irrigated area in 1950/51 to 63 per cent in 2018, with 90 per cent of the water withdrawn used for irrigation (Jain et al. 2019). The climate mitigation options for groundwater irrigation include rationing the electricity supply, adopting micro-irrigation technologies, improving pump efficiency, improving on-farm irrigation efficiency, and managing aquifer recharge (Karimi et.al. 2012; Shah 2009).

6.3 Water dependence

As explained in the previous section, the mitigation potential of forests, natural grasslands, pastures, and croplands depends on an intact and functioning water cycle. Water is the main limiting factor for vegetation growth in many parts of the world, especially where there are periodic droughts (Knapp et al. 2002; Smith and Knapp 2001). Climate change is likely to bring more frequent and longer periods of drought, with negative effects on primary production and increased risk of biodiversity loss. Climate change presents a substantial risk to the stability of land carbon stocks and sinks (Anderegg et al. 2020) and reduced vegetation cover is therefore likely to be associated with a net loss of soil carbon and, over the long term, a positive feedback mechanism for climate change. Thus, large-scale shifts in vegetation cover can change global climatic conditions by altering the surface energy budget, leading to deterioration in local water resources (Pielke et al. 2002).

6.3.1 Mitigation measures in forests

Forest-based mitigation measures depend fundamentally on a functional water cycle. An altered water cycle can lead to droughts, floods, and reduced water quality, reducing tree growth and survival, and hence decreasing carbon sequestration. It may also threaten the very existence of a forest ecosystem, thus reducing existing forest carbon sinks. For instance, tropical forests and savannas are both possible biomes (i.e., ‘alternative stable

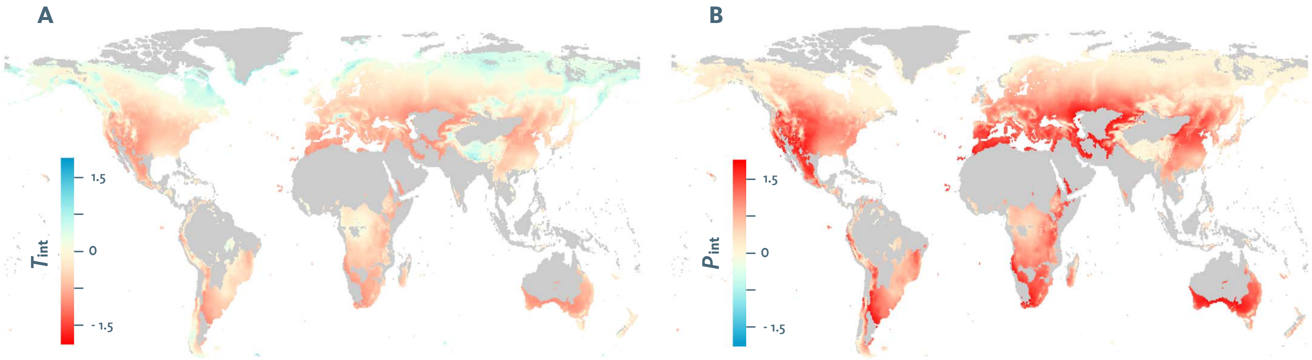

Figure. 6.8. Tree growth responses to climate changes in A. temperature and B. precipitation, based on tree-ring data sampled from 2,710 sites between 1930 and 1960. Red colours indicate strong water constraints and blue colours indicate strong energy constraints. Source: Babst et al. (2019).

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 feedback loop of climate change involving increased aridity, droughts, and fires may induce abrupt and potentially irreversible change in a biome state (Staver, Archibald, and Levin 2011).

After sunlight and temperature, water availability is usually the most limiting factor for tree growth. Tree productivity is limited by water in many parts of the world, but to the greatest extent in the low to mid latitudes (Figure 6.8). Afforestation in arid and semi-arid regions is particularly prone to water limitations. For example, afforested areas in Mongolia have been shown to suffer from water deficit (Wang et al. 2020), while the Loess Plateau in China may need to substantially adjust the water balance in the future depending on uncertainties in climate change, precipitation change, and water demand (Feng et al. 2016; Zhang et al. 2018).

Carbon uptake in tropical forests declines considerably in dry years (Doughty et al. 2015), while drought events may cause carbon release at a level several times higher than the annual carbon sink in tropical forests (Lewis et al. 2011). However, it should be noted that in many boreal regions, water availability may already have replaced energy as the dominant limiting factor (Babst et al. 2019) and in scenarios of severe climate change (RCP8.5.), increasing temperatures and droughts could have detrimental effects on tree growth and thus carbon sequestration ability. Furthermore, drought events have a disproportionately large impact on the mortality rates of large trees (Bennett et al. 2015; Phillips et al. 2010) and, therefore, a disproportionate impact on carbon emissions and storage (Bastin et al. 2015; Corlett 2016; Fauset et al. 2015). Hence, detailed consideration of water constraints (including water demand, hydroclimatic change, planting densities, and tree species selection) is necessary to avoid overestimating the sustainable level of reforestation and afforestation for carbon sequestration.

Plantations often involve fast growing, water-intensive tree species (such as most pioneer species) that require high water availability (Cao et al. 2016; Silveira 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 carbon capture and storage (as required for 1.5°C target scenarios) will require water withdrawals for irrigation of between 400 and 3,000 cubic km per year, 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 Mitigation measures in natural grasslands, pastures, and croplands

As with forests, the full potential of climate mitigation in natural grasslands, pastures, and croplands can be reached only with an intact water cycle and sufficient freshwater. Measures to restore, conserve, and sustainably manage vegetation cover and soil carbon stocks depend on freshwater. If implemented correctly, these measures can, in turn, 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 reducing input costs (Beare et al. 1994; Li et al. 2019).

Climate change affects not only the amount of water available, but also how it is distributed across the year. Less predictable seasonality and shorter wet seasons mean less likelihood of multiple cropping, reducing crop intensity and increasing pressure on cropland expansion. Natural grasslands, pastures, and croplands are sensitive to shifts in the local climatic regime, and climate change strongly impacts the survival and distribution of plant species, which in turn increases ecosystem vulnerability, promotes fires and soil degradation, and hampers primary production. Climate change has already strongly altered local and regional water cycles in many places, causing changes in precipitation patterns with more frequent and intense droughts and floods. These changes have impacted carbon sequestration and storage, and methane emissions in agricultural land. In some regions, climate change induced drought events have hampered crop production, while in others large floods have inundated agricultural land causing crop loss, soil erosion, pollution, and the spread of invasive species (Warner et al. 2017).

Drought and land-use change have a direct impact on the carbon source and 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 has dramatically altered the structure and function of grassland ecosystems. Regional gradients in rainfall affect the distribution of major grassland types, mean root depth, and root productivity, which in turn affect soil organic carbon storage and other soil properties and processes. Grassland degradation can cause extensive soil erosion, especially during extreme events such as flooding (Lal 1995). The fine root system of grassland stabilizes topsoil and contributes to soil carbon sequestration. As a result of grassland degradation, topsoil can be washed away during heavy rain events or blown away by winds, which may also cause major problems for agriculture (Boardman and Vandaele 2010). To mitigate climate change, sustainable land use management practices, approaches, and strategies can improve grassland resilience to environmental impacts such as droughts and wildfires and regulate the carbon storage capacity of grassland soils. Box 6.4 explains different concepts to estimate water demand in agriculture, which may be useful when assessing the role of freshwater in climate mitigation in natural grasslands, pastures, and croplands.

Potato crops decimated from drought. Source: Shutterstock.

Box 6.4. Crop production, virtual water, and water footprints

As noted earlier in the chapter, crop production is a water-intensive activity, with 70 per cent of all water used globally applied in agriculture (FAO 2017). To obtain a more accurate representation of water use in agricultural production, Tony Allan developed the concept of 'virtual water' (Allan 1999; 2011), which includes all water used during the production process, thus becoming 'embodied' in the product.

Through trade in agricultural commodities, virtual water flows through an intricate global web. Many scholars have explored how these virtual water flows can be understood to improve global water-use efficiency in agricultural production, and ease environmental constraints by utilizing the best suited production sites (e.g. Hoekstra 2003; Hoekstra and Hung 2005; Yang et al. 2006). Based on this logic, Allan argued that water-scarce nations should import the most water-intensive food products 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 et al. 2011; Yang et al. 2006).

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 been picked up primarily by businesses seeking to assess the water going into their different products and to set quantitative targets to improve water-use efficiency per unit of product (Rudebeck 2019).

As an example of the application of this concept, the water footprint has been used at catchment scale in the semi-arid tropics in Kenya (Van der Laan et al. 2021). The assessment covered two agricultural products (maize and roses). The water footprint for maize was estimated to be 6.6 times higher than for roses. It was concluded that a water footprint assessment may help the various water users to better appreciate the finite amount of produce that can be produced in a season from a shared resource, including trade-offs.

While these concepts are appealing, there are issues with relying too heavily on water footprint assessments to determine the typical or average amount of water in a product, and its subsequent water impact. Firstly, the assessment often does not account for whether the crop is irrigated or rainfed (i.e., blue or green water). Secondly, the same crop may require different quantities of water depending on where it is grown, so the actual footprint can vary considerably depending on the climate and management conditions. 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 to influence water management practices in agriculture can therefore be problematic if details are not provided.

6.4 Water impacts

6.4.1 Mitigation measures in forests

Cross-continental impacts

Over time, the effects of afforestation and reforestation on the hydroclimate can be complex due to interactions with climate change and other types of land-use change (Teuling et al. 2019). In comparison with grasslands, croplands, and other short vegetation types, the relatively high evapotranspiration rates of forests (particularly during dry periods) means they have greater potential to generate the ecosystem service of providing moisture for downwind rainfall (Keys, Wang-Erlandsson, and Gordon 2016). In areas where a large share of water evaporation is returned as precipitation over land, protecting forests may also mean protecting downwind rainfall (Figure 6.9). Current levels of human deforestation have resulted in lower rates of precipitation when compared with a scenario of 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 the Amazon and Congo

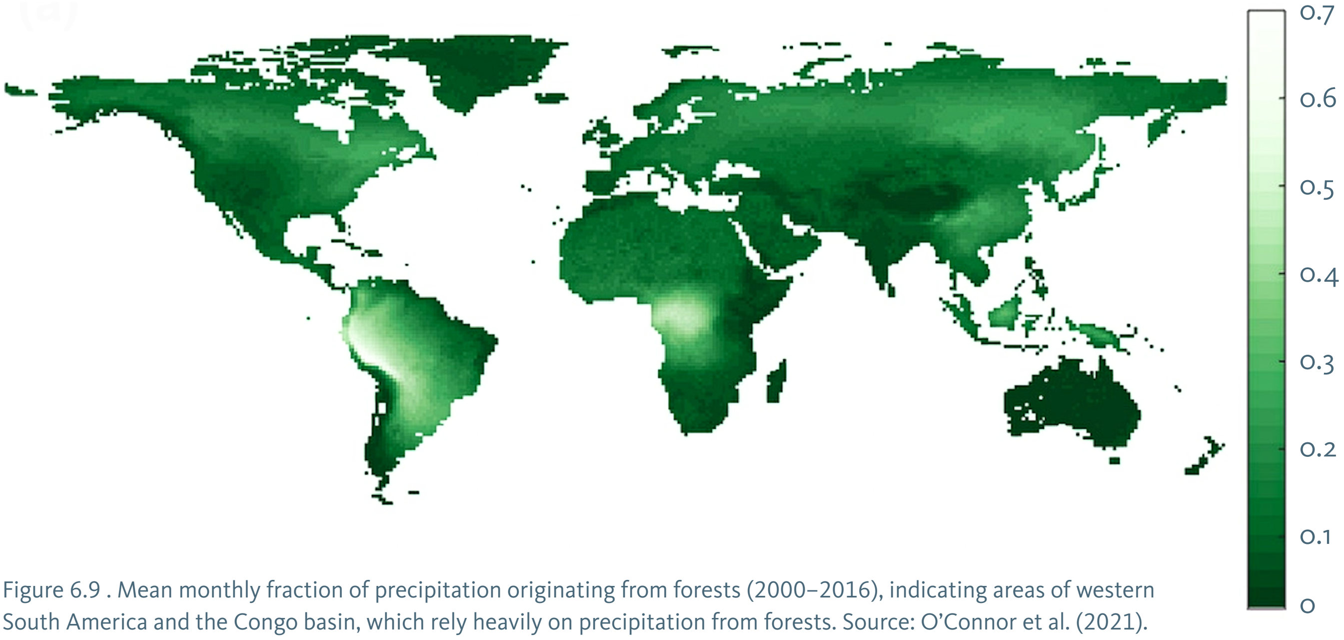

Figure 6.9 . Mean monthly fraction of precipitation originating from forests (2000–2016), indicating areas of western South America and the Congo basin, which rely heavily on precipitation from forests. Source: O'Connor et al. (2021).

rainforests, a substantial portion of rainfall is generated by 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 having an adverse impact on crop yields and ecosystems downwind of the rainforests (such as in the Brazilian Cerrado biome 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 by maintaining the rainfall needed to support 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; Ilstedt et al. 2007). Forests have higher evapotranspiration than shorter vegetation types such as grasslands and shrublands (Zhang, Dawes, and Walker 2001). Trees and forests can improve the hydrological functioning of degraded soils, particularly through enhanced soil infiltration capacity and preferential flow (Bargués-Tobella et al. 2014; 2020; Benegas et al. 2014; Bonnesoeur et al. 2019; Filoso et al. 2017; Ilstedt et al. 2007; Leite et al. 2018; Lozano-Baez et al. 2019). Hence, afforestation and tree-based restoration of degraded lands may have a less negative impact on groundwater recharge and dry season flows than predicted by most of the available scientific evidence (Krishnaswamy et al. 2013; Ogden et al. 2013; Zhou et al. 2010), in particular under intermediate degrees of tree cover (Ilstedt et al. 2016) as may 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 or reforestation from short vegetation types may help reduce such risks (Lee et al. 2018; Salvati and Carlucci 2014; Wang et al. 2016). Finally, cloud forest restoration and reforestation in locations exposed to moist winds and frequent cloud cover can have positive effects on water yields by increasing cloud-water interception (Bruijnzeel and Bruijnzeel 2001; Bruijnzeel, Mulligan, and Scatena 2011; Ghazoul and Sheil 2010).

Tree planting, 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, particularly in dry areas and during dry periods (McVicar et al. 2007; Mu et al. 2007; Wang et al. 2020). For instance, a study examining potential improvements in water provision by analysing changes in annual streamflow in forest restoration and other forms of forest cover expansion showed an 80 per cent decrease, as well as an increase in 6 per cent of the cases (Filoso et al. 2017). The use of longer rotation periods and species selection, by promoting tree species that consume less water and/or are more effective at improving soil hydrological functioning for instance, can also be effective in reducing the observed negative impacts of afforestation on streamflow (Ferraz, Lima, and Rodrigues 2013; Scott and Prinsloo 2008). Further improvements in water yields may be achieved through such other ecohydrological-based forest management practices 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; Bayala 2002; del Campo et al. 2017; 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. 2013; Ghimire et al. 2014; Lulandala et al. 2022). Hence, controlling and minimizing the impact of these activities, through grazing exclosures for instance, should be a priority.

6.4.2 Mitigation measures in natural grasslands, pastures, and croplands

The water and carbon cycles of an ecosystem are strongly interlinked, for example through the role of above- and below-ground biomass in carbon cycling. Mitigation measures in natural grasslands, pastures, and croplands generally aim to improve vegetation cover and thus have a positive influence on soil moisture. Vegetation cover can reduce water evaporation by shading the soil and regulating soil temperature; reduce the magnitude of water erosion by diminishing the impacts of rainfall, run-off, and flood events; and reduce streamflow and sediment export by intercepting run-off and improving water infiltration. For instance, the trees in agroforestry systems can influence the capacity of the soil to capture, store, and release water, as organic matter from trees enhances soil water-holding capacity and improves soil structure and porosity (Benegas et al. 2015).

In some cases, misguided implementation of climate mitigation measures in natural grasslands, pastures, and croplands may disrupt water flows and reduce freshwater availability, thus risk causing local water shortage, biodiversity loss, and harm to local communities. As an example, in grasslands and savannas throughout the tropics, carbon mitigation programmes often promote fire suppression and forest expansion, although these can have negative effects on biodiversity and ecosystem services (Abreu et al. 2017; Veldman et al. 2015).

There are large areas of agricultural land under irrigation across the globe. Irrigation can be a promising practice to promote vegetation growth which can increase the storage of soil organic carbon (SOC) and thus may have positive effects on climate mitigation. The effect of irrigation agriculture on SOC depends on different factors, such as climatic zone, soil type, agricultural management practices, soil depth and type of crops, as well as water quality (Antón et al. 2022; Tiefenbacher et al. 2021; Emde et al. 2021; Eshel, Fine & Singer, 2007). In one review study, the greatest increase in SOC (14.8%) was observed at a soil depth of 0–10 cm on irrigated semi-arid sites (Emde et al. 2021).

As in forest systems, species selection is an important part of climate mitigation measures in croplands and grazing lands, especially in arid and semi-arid regions. Species that are sensitive to water stress or have high demand for water should be grown only in areas that do not experience water stress and periods of drought. In situations where water-demanding species are needed, sustainable management options can reduce water scarcity risk. Agroforestry and other climate-smart integrated farming systems include shade crops, crop rotations, cover crops, and integrated crop-livestock or crop-livestock-forestry systems (Kakamoukas et al. 2021; Niggli et al. 2009). Technical measures to improve water-use efficiency include micro- or drip irrigation (Parthasarathi et al. 2021).

6.5 Co-benefits and trade-offs

The previous sections explain how land-based measures to mitigate climate change (i.e., protection, restoration, and sustainable management of terrestrial ecosystems) affect the water cycle. Often, this impact can be identified as either co-benefits or trade-offs. In addition, land-based mitigation measures have co-benefits for climate adaptation and resilience as well as for improving other ecosystem services such as biodiversity, plant productivity, and soil health. For all these additional co-benefits, freshwater availability and a reliable hydrological cycle are fundamental and thus there may be multiple synergies between climate action, water security, and ecosystem processes and services (Boltz et al. 2019). One example of key importance for regulating the Earth's energy, water, carbon, and nutrient cycle dynamics is to halt deforestation and ecosystem degradation to reduce GHG emissions and help preserve water cycle dynamics. Another is how the mitigation potential of land-based measures, including many nature-based solutions, is highly dependent on their ability to adapt to increased global warming, and land-based adaptation potential is strongly interlinked with freshwater availability and a reliable hydrological cycle. There is evidence that hydrological changes are already pushing some ecosystems and ecological processes towards irreversible change, such as retreating glaciers or tropical forests converting to savanna. The multiple co-benefits provided by terrestrial ecosystems in addition to carbon sequestration can offer synergies for human well-being, ecosystem health, and climate resilience; with examples including flood and other disaster risk reduction, biodiversity recovery, agricultural production, sustainable livelihoods, and water quality improvement (Raymond et al. 2017; UN Water 2018).

Although multiple co-benefits are generally provided by land-based mitigation measures, there may be trade-offs to be considered. Land degradation is a major contributing factor to climate change and, at the same time, some drivers of degradation, such as soil erosion, increased risk of forest fires, and increased expansion of invasive species, will be exacerbated by climate change (Kotiaho et al. 2018). When implementing ecosystem protection and sustainable management practices, land managers are often faced with challenging trade-offs due to constraints in tackling the drivers of degradation, such as increasing demand for agricultural land, urbanization, aquaculture, and coastal development (Epple et al. 2016). These drivers of degradation must be addressed since they may pose limitations to ecosystem protection in climate and development planning. These challenges can be overcome, for instance by strengthening monitoring, ensuring reliable data evaluation, and establishing sustainable land management systems.

6.5.1 Human well-being and social development goals

Addressing questions of how, where, and why climate mitigation measures are implemented must consider the broader political economy and place people at the centre of proposed solutions. The choice of mitigation measures often reflects the different political interests and ideas underlying development and the forest sector (Brockhaus et al. 2021; Di Gregorio et al. 2017), resulting in policy measures to reduce deforestation and degradation disproportionately targeting smallholders and shifting cultivation over political priority for large-scale industrial development (Skutsch and Turnhout 2020; also see Ingalls and Dwyer 2016 for a case in 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 conceptualized typically as balancing biodiversity conservation with human well-being or broader development objectives. As such, many recent conservation or mitigation interventions have been designed with a view to 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 a large scale, there will be a more plausible range of outcomes beyond a change in emissions output (Bustamante et al. 2014) and this inevitably affects a vast range of interested stakeholders. Experiences gained over the last few decades have indeed shown that win-win outcomes are the exception rather than the norm (McShane et al. 2011; Muradian et al. 2013; Sunderland et al. 2008) and interventions typically result in trade-offs and may incur unintended negative outcomes. Indeed, even initiatives that have been touted as win-wins have been revealed upon closer analysis to generate negative impacts. In addition, a systematic review 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 (Malkamäki et al. 2018).

It is important to note that the effects of mitigation measures are site specific and therefore it is challenging to generalize the types of trade-offs to expect or synergies to optimize. However, in designing such initiatives it can be useful to characterize potential outcomes across the institutional, socio-economic, and environmental dimensions (Bustamante et al. 2014,

Seedlings for reforestation of the Atlantic Forest, in Rosario do Limeira, Brazil. Source: Shutterstock.

Reed et al. 2020), and to 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, inequities, or social-environmental injustices will also be needed if these measures are to gain legitimacy and ownership at all scales.

Regions identified as having opportunities for reforestation and afforestation measures are not ‘empty’. On the contrary, one-third of the population in the tropical global South (around 1.01 billion) lives within 8 km of land identified as having potential for forest restoration (Erbaugh et al. 2020). Depending on design, the breadth of stakeholder engagement, and the level of prioritization to local people, each mitigation measure can, and possible 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 programme could contribute to emission reductions but is also likely to affect local land tenure and/or create conflicts relating to resource use, food production, water and soil quality, local adaptive capacity, and conservation of biodiversity. The extent to which these are positive or negative impacts will depend on the contextual conditions and institutions in place (et al. 2013). Furthermore, trade-offs and synergies can occur both within and between sectors and generate further feedback loops (both site-specific and distant) over time.

There has been weak interest in working with ecosystem services in agriculture (Sanou et al. 2023). One reason could be that external inputs have been focused on boosting provisioning services, such as yields, while the costs have been placed on public goods (regulating and supporting ecosystem services) in terms of degraded and overused resources, including water and land. Regulating and supporting ecosystem services often entails temporal and spatial scales far beyond the farm unit or growing season, which makes the impact assessment more complex than that of a well-defined farm, or field decisions usually taken by individual farmers or land-use planners. Most tools to assess trade-offs between agricultural productivity and other ecosystem services address only one or a bundle of ecosystem services relating to water, biodiversity, or climate regulation, and are often designed for different types of land use and ecosystems and applicable at different scales. One way forward could be closer collaboration between practitioners, development organizations, non-governmental organizations, and scientists to foster the co-development of tools to assess trade-offs and identify sustainable strategies for closing the yield gap, increasing productivity, and balancing the ecosystem services included in the SDG framework (Sanou et al. 2023; Tenge et al. 2007). Box 6.5 describes the potential for positive forest conservation in indigenous and tribal territories.

Box 6.5. Positive forest conservation in indigenous and tribal territories

A recent study by the Food and Agriculture Organization of the United Nations (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 'other effective area-based conservation measures' 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 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 territories and address the continuous pressure on them, new investment and policy initiatives should include and support the strengthening of communal territorial rights, compensation for environmental services, community forest management, cultural revitalization and traditional knowledge, and territorial governance and stronger indigenous organizations.

6.6 Policy status

Forest and water issues discussed in the academic community have focused mainly on the 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 account of water have been developed either in the forest or the water sector 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 the forest, water, and climate link has started to be taken into account, or at least acknowledged, in policies (Springgay et al. 2019). This means that while there is some advancement in policies concerning forest-based mitigation measures and water, much work remains to be done.

6.6.1 Increasing attention on the links among climate change, forests and water

The forest and water relationship started gaining momentum in 2002 with the Shiga Declaration on Forests and Water, in which experts highlighted the need for a more holistic approach to policies and management of forests and water (FAO 20002). 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, including forests, water, and climate change (FAO 2002). This sparked a number of global and regional events, which have continued up to the present and catalysed action and discussion on the link between climate change, forests, and water (FAO 2002; Springgay et al. 2019).

Although water shortage represents a growing problem for rainfed agriculture, there is still little integration of water issues into policy frameworks, even within the agriculture sector. Managing water resources requires coordination and policy coherence across sectors and locations, as well as effective governance to manage interdependence and trade-offs between them. Agriculture plays a central role through the landscapes it covers 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 relating to forests and other land use as mitigation measures have been driven mostly by the United Nations Framework Convention on Climate Change (UNFCCC) processes, namely the Kyoto Protocol, the Paris Agreement, and, most recently, the Koronivia Joint Work on Agriculture. The main aim of the latter is to mainstream the unique potential of land systems to address climate change by driving transformation in agricultural systems, and addressing 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 Plans (NAPs). However, when it comes to mitigation measures that include the link between land systems and water, it is important to look beyond the UNFCCC agreements since other global processes have played a significant role in the advancement of policies and measures that address this link, providing additional important entry points. This section explains how policy-related measures have evolved and highlights some of the remaining gaps.

6.6.2 Governance frameworks

Global governance frameworks including land-based mitigation measures that also address water have come from various areas of work such as the implementation of the different conventions and United Nations processes. These include the United Nations Convention to Combat Desertification (strategic objectives 1 and 3 in particular), the Convention on Biological Diversity and its recently adopted Kunming-Montreal Global Biodiversity Framework (targets 2, 3, 10, and 11 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 strategic plan includes 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 current most important 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 have evolved, they have aimed to align their work with each other and with other global frameworks such as the 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 that considers human rights for a more equitable distribution of water (IPCC 2019). For degraded cropland and soils, 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. Land degradation

Rusting boat carcasses in the desert, once the Aral Sea, between Kazakhstan and Uzbekistan. Source: Shutterstock.

neutrality applies sustainable land management practices to maintain or enhance soil organic carbon, avoiding or reducing future land degradation, while reversing previous degradation at the same time. Farmers can implement the land degradation neutrality framework while mitigating climate change by adopting sustainable land management approaches and technologies, such as erosion control, soil organic carbon sequestration, and water conservation (Chotte et al. 2019). At the 21st Conference of the Parties to the UNFCCC (COP21), the '4 per 1000' Soils for Food Security and Climate initiative was launched with an aspiration to increase global soil organic carbon stocks by 0.4 per cent per year in compensation for the global emissions of GHG from anthropogenic sources.

With respect to the forest-land-water nexus, a study by Springgay et al. (2019) evaluated 168 NDCs (and Intended NDCs, the earlier versions) to determine the extent to which they include forest- and land-related water resources management. The results showed that 45 per cent of those evaluated referred to keywords related to the forest-land-water nexus, while 57 per cent included agricultural measures within their mitigation sections. Since that study, the NDCs have been updated and a recent study by the Stockholm International Water Institute shows encouraging results on the evolution and coverage of the NDCs (see Box 6.6; also see Boxes 3.1 and 3.2 in Chapter 3).

Box 6.6. Integration of land-based mitigation measures in NDCs

Forests

Forest-based policies and measures were included in in 65 per cent of enhanced NDCs from non-Annex 1 countries[2] and form a significant part of mitigation strategies. In addition, measures that specifically referenced nature-based solutions were found in 45 per cent of non-Annex 1 NDCs, focused mostly on the increased role of forests and mangroves, especially in terms of their mitigation potential. However, recognition of the role of water in maintaining forest ecosystems or the connection between water resources and forest management was rare in mitigation sections, even among the Parties that acknowledged the possible connections between water and climate change within their adaptation sections.

While adaptation sections contained 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 and rehabilitation, sustainable forest management or similar, legal forest protection, and reductions in the rate of deforestation and/or reducing deforestation and forest degradation (REDD) and REDD+[3] measures. Of the enhanced NDCs from non-Annex 1 countries that included forest measures within their mitigation sections, reforestation activities were cited most frequently, followed by sustainable forest management (73 per cent) and restoration/rehabilitation of forest lands (67 per cent). Measures relating to afforestation or plantations were included in 60 per cent of enhanced NDCs, while measures relating to reducing the rate of deforestation and/or REDD+ activities were found in just over 50 per cent of the NDCs that included forest measures.

The final type of measure, forest protection, was found in one-third (34 per cent) of the NDCs that included forestry measures. One or more forest mitigation measures were found in the plans of almost all sub-Saharan African countries evaluated (35 as of January 2022), while most Latin American countries (18 as of January 2022) also included forest mitigation measures.

Very few forest mitigation measures included water components specifically or recognized the role of water in maintaining forest ecosystems or the provision of water-related ecosystem services from forests. Reforestation and afforestation can have a significant impact on hydrological systems, but such connections were not raised in mitigation sections. The main exception was the limited number of NDCs that included riparian restoration or mangrove forests within their mitigation sections.

As well as forestry activities, approximately 45 per cent of the enhanced NDCs included measures to promote 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 five new protected areas to complement the existing government commitment to increase forest protected areas to 1.5 million ha, ensuring a 3 km buffer zone, by 2030. Reduce emissions by 210 Gt CO_2-e 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 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.

Natural grasslands, pastures, and croplands

Of the 114 enhanced NDCs evaluated, 57 per cent 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 NDCs 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 included 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 per cent of enhanced NDCs 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 have implications for water resources irrespective of the means of generation. Such interactions were not recognized 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 100 ha in 2030. Improvement of agricultural soil practices help storing carbon in soils in areas that increase progressively to 20 per cent of cultivated cropland in 2030. In 2030, the application of this measure allows a reduction of emissions estimated at 167 kt CO_2-e per year compared to the ‘business as usual’ scenario.
- **Liberia:** Deploy at least one solar water pump and/or spring irrigation system for crop irrigation for communal farms with land constraints in each county by 2030. 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 per cent to total agricultural emissions (in 2015). Thus, introducing measures for reducing soil emissions will be a key aspect for South Sudan.

Source: UNDP-SIWI Water Governance Facility (2023).

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2. Parties to the UNFCCC not listed in Annex I of the convention are mostly low-income developing countries.
3. REDD+ includes additional conservation and climate change mitigation measures.

Several initiatives have been launched at the global and regional levels to catalyse action on forest- and land-based mitigation. Global initiatives include the United Nations Decade on Ecosystem Restoration (see Chapter 3) and the Bonn Challenge, a global initiative aiming to restore 150 million ha of degraded and deforested landscapes by 2020 and 350 million ha by 2030 (Dave et al. 2018). 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. More recently, the Glasgow Leaders' declaration on forests and land use at the UNFCCC COP26 committed world leaders to working together to halt and reverse forest loss and land degradation by 2030 and provide substantial political support to accelerate action. The declaration does not mention water specifically, but it does emphasize the role of forests in maintaining ecosystem services.

Regional initiatives play a particularly important role as they can provide an effective means for regional and transboundary cooperation with actions targeted specifically to address regional and local challenges. Relevant initiatives include the Great Green Wall for the Sahara and the Sahel initiative (see Box 6.2) as well as regional initiatives under the Bonn challenge such as the African Forest Landscape Restoration Initiative (AFR100), Initiative 20x20 in Latin America and the Caribbean, and ECCA30 (which aims to restore 30 million ha of degraded and deforested land in Europe, the Caucasus, and Central Asia).

6.6.3 Regulatory instruments

Global governance frameworks provide the basis for national and subnational processes that establish regulatory instruments. Their success 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, and restrictions in use and access (i.e. protected areas). While many of these instruments may not have been developed initially for climate change mitigation specifically, they clearly address or have an impact on what we now consider as land-based climate mitigation measures.

While there have been vast improvements in the management of protected areas, other effective area-based conservation measures are increasingly being considered as an alternative. They have been recognized and encouraged under the Convention on Biological Diversity since 2010 and are defined under its 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 other effective area-based conservation measures in national legal frameworks and supporting mechanisms that, for example, limit industrial development or natural resource extractions, can prove to be an effective regulatory instrument in key areas for forest-based mitigation actions including water management, such as forest conservation and restoration.

While relevant regulatory instruments may not be framed as climate mitigation instruments per se, instruments developed under different sectors and 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 management that uses a landscape approach. Furthermore, regulatory instruments should be accompanied by economic and financial mechanisms and incentives (see the next section).

6.6.4 Economic and financial mechanisms

Effective climate mitigation strategies and policies should always integrate regulative and informational instruments with financial mechanisms. This section gives a brief overview of the policies and market-based instruments that can be classed as 'carrots' (e.g., rewards, incentives, payments, and blend-finance) to promote success in forest-based mitigation measures.

Most of the literature on market- 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 allows for greater integration and cooperation between the agroforestry and water sectors as these approaches are often based on a multi-stakeholder dialogue among land managers and other resource-dependent industries (e.g., utilities, hydropower, irrigation, etc.). Furthermore, it has been suggested that PES schemes 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+ 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 played by the public sector, which can intervene as a buyer (as in the case of agri-environment schemes in the EU and USA) and/or as a legal actor providing a framework with an obligation to offset emissions or other resource use (scope taxes, Emission Trading Scheme, etc., see Table 6.5).

Table 6.5. 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 implemented at international, national, and regional levels. Examples of regulated markets include UNFCCC's REDD+ mechanism and the three mechanisms of the Kyoto Protocol: the Clean Development Mechanism, the Joint Implementation and the EU Emissions Trading Scheme.
	Agri-environment schemes	These are well-known in the Australia, Europe, and USA, and can be traced back to the 1970s, before the PES concept was conceived. They are typically national/continental incentives schemes, with little targeting and additionality. However, they constitute the main type of scheme for western countries, often incentivizing tree planting, hedgerow maintenance, fire control, and sustainable forest management for water quality. Some 90 per cent of EU funding for forests comes from the European Agricultural Fund for Rural Development.
	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, mainly but not exclusively in the hydropower and drinking water sectors. The funding generated is often associated with an obligation to reinvest the revenues into forest and catchment restoration activities. This is the case for several water funds in Asia and Latin America that rely on water charges as a 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. They usually work with private forest carbon certification standards (such as Gold Standard, Verified Carbon Standard, Verra carbon standards, etc.) where reforestation projects certify a certain amount of CO_2 stored by producing 'carbon credits', and carbon brokers then place these credits on the private market for CO_2 offsetting. In 2021, the voluntary carbon credit market exceeded USD 1 billion for the first time and is projected to increase 15-fold by 2030 (Forest Trends' Ecosystem Marketplace 2021).
	Voluntary certification schemes	In these schemes, producers send a signal to consumers that environmental impacts are positive (in relative terms) and consequently gain a premium on the market price. The best known are the Forest Stewardship Council (FSC, with 230 million ha certified forest area) and the Programme for the Endorsement of Forest Certification (330 million ha). Since 2018, FSC has developed a specific procedure to verify ecosystem services impacts and allow for registered sponsorship and claims. A recent Worldwide Fund for Nature report highlights the new FSC strategy on PES development (WWF 2022), which relies on short ecosystem services value chains, which build direct connections between forest managers and communities, and sponsors.
	Investment blended funds	These are private funds such as environmentally focused bonds, loans, or equity, funded by impact or philanthropic investors that support green-grey infrastructure projects to fulfil their impact-oriented missions while expecting a return on the investment generated by cost saving from reduced operational costs. These funds may also be public, such as the Land Degradation Neutrality and the European Investment Bank Natural Capital Financing Facility. These funds are often coupled with technical assistance and grants funds to deliver blended-finance programmes.

Banana and eucalyptus agroforesty plantation. Source: Shutterstock.

Where the state does not intervene, the private market may step in (with voluntary carbon and ecosystem services markets). PES markets provide funding mainly for forest mitigation relating to carbon, water, and biodiversity offsetting, which are the main ecosystem services required by the private sector. Table 6.5 summarizes the main funding mechanisms available for forest- and land-based climate mitigation measures. Various relevant financing mechanisms of the UNFCCC and other multilateral environmental agreements are addressed in Chapter 3, such as the Global Environment Facility, the Green Climate Fund, the Land Degradation Neutrality Fund and the Global Biodiversity Framework Fund.

Economic and financial mechanisms are being promoted by policymakers, scientists, and the private sector, with considerable numbers of initiatives, case studies, and best practices available for scrutiny. However, relevant, effective, and large-scale instruments based on the private market are often lacking or remain in the development stage. Nevertheless, an improving trend is clear, especially after COP26, where the Glasgow Leaders' Declaration on Forests and Land Use committed 141 countries representing 90 per cent of global forests to "significantly increase finance and strengthen financial commitments from both public and private sources". COP26 has also opened the door to carbon credits generated by the private sector to offset within the regulated market. In 2022, the European Commission released its carbon farming initiative, regulating public and private land-based carbon markets in the EU. Moreover, many private initiatives such as the Science Based Targets Network are building new market demand for water and biodiversity offsetting under the 'nature positive' concept. This will play an important part in boosting the future of these instruments, with the hope that these incentives will build on strong benefit-sharing mechanisms and 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 encompass water management are moving towards more holistic and multisectoral approaches in governance frameworks, regulatory instruments, and financial mechanisms. While it is encouraging to see advancements in this direction, gaps remain, especially when it comes to national and local implementation. Closing these gaps will depend on strengthening the science-policy interface by using the most up-to-date science and considering the complex and potentially cross-scale feedback loops of land-based mitigation measures, as well as the potential trade-offs and synergies among different benefits and constraints. Systems thinking and integrated landscape management approaches can be useful in this context (Seddon et al. 2020; Farooqi et al. 2020).

Furthermore, it is important to consider the relationship between land-based mitigation measures and water management at different scales of governance. At the local and sub-national scales, policies and management plans often account for the water impacts of forest-based mitigation measures on blue water (e.g., as part of catchment management or national adaptation programmes (Pramova et al. 2012) but other aspects of water-related dependency, impact, and feedback are seldom considered (Ellison et al. 2017). For instance, proposals for integrative management and consideration of atmospheric processes are yet to be linked with policy and governance in climate mitigation contexts, and more work is needed to assess how these concepts can be integrated in existing mitigation measures such as the Clean Development Mechanism, REDD+, and NDCs.

As global governance frameworks move forward, it is also important to consider all available information and tools to improve indicators, methodologies, and monitoring to achieve global goals. For example, the process of refining the SDG indicators and their methodologies is an evolving process that needs to be reviewed periodically in accordance with the United Nations General Assembly Resolution A/RES/71/313. Also the NDCs are reviewed every five years, which provides an opportunity to build and improve on previous NDCs and to revise national policies to ensure that targets are met.

6.8 Conclusions and 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 is a substantial risk of unrealised mitigation potential and negative impacts on other water, biodiversity, social equality, and other sustainability goals (see section 6.5). As such, there is a need to ensure systems thinking in the management and governance of land systems mitigation measures that account holistically for interconnected issues relating to water constraints, land availability, carbon sequestration, biodiversity implications, local livelihoods, and regional development, for example.

Land-based climate mitigation has a high carbon emission reduction potential, which is linked intrinsically with the water cycle. Of the various mitigation measures, the prevention of deforestation, and forest and land degradation has historically received the greatest attention and investment. However, while commitment to reducing deforestation remains high on the global policy agenda, the past decade has also seen an increasing focus on forest and landscape restoration through multilateral environmental agreements and other initiatives, such as the Bonn Challenge and the United Nations Decade on Ecosystem Restoration. So far, these measures and mechanisms have been focused on carbon management. More recently, however, there has been increasing interest in co-benefits related to water and biodiversity, from both an ecological point of view and market demand in relation to current nature-positive targets.

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

All land-based mitigation measures must account for the water risks and water cycle changes that are already occurring under climate change, including a reduction in regional and global agricultural productivity, irreversible damage to biodiversity, and conversion of forest carbon sinks into carbon sources. All climate mitigation measures must account for their social and environmental justice implications to local populations. Land-based mitigation measures are also integral to non-local drivers of forest-land-water systems and require consideration of the links with trade, migration, hydroclimatic teleconnections, and international frameworks, for example. This chapter shows the importance of adopting large-scale system dynamics thinking and an integrated approach to land-based mitigation to achieve the best possible climate and sustainability benefits. All financial mechanisms and public policies should support holistic approaches, avoiding to only focus on carbon and instead integrate water and biodiversity conservation as key goals and co-benefits, ensuring benefit-sharing with local communities.

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