Cross-Chapter Paper 7: Tropical Forests

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Executive Summary

Over 420 million ha of forest were lost to deforestation from 1990 to 2020; more than 90% of that loss took place in tropical areas (*high confidence*), threatening biodiversity, environmental services, livelihoods of forest communities and resilience to climate shocks (*high confidence*[1]). Forty five percent of the world's forested areas are in the tropics, and they are amongst the most important regulators of regional and global climate, natural carbon sinks and the most significant repositories of terrestrial biomass. They are of immeasurable value to biodiversity, ecosystem services, social and cultural identities, livelihoods, and climate change adaptation and mitigation {CCP7.2.1; CCP7.2.2; Box CCP7.2; Table CCP7.2}

Climate change affects tropical forests through warming and increased occurrence of extreme events such as droughts and heat waves, as well as more frequent fires, which increase tree mortality and reduce tree growth, limiting the ability of forests to regenerate (*high confidence*). Climate change is altering the structure and species composition of tropical tree communities (*high confidence*), including transitions from moist to drier forest in regions such as the Amazon (*high confidence*), and movement of species from lower to higher elevations (*high confidence*). Despite CO_2 fertilization, ongoing climate change has weakened the carbon sink potential of tropical forests in Amazonia and, to a lesser extent, in Africa and Asia (*medium confidence*). {CCP7.2.3; CCP7.3}

Large-scale tropical deforestation affects regional to continental scale climates with significant impacts on forest resilience (*high confidence*). Deforestation generally reduces rainfall and enhances temperatures with effects depending on scales (*high confidence*), while often increasing surface runoff (*medium confidence*). Continued deforestation-driven landscape drying and fragmentation will aggravate fire risk and reduce forest resilience, leading to savannization of the tropical forest biomes, in particular in combination with climate change (*high confidence*). {CCP7.3.6}

Implementing sustainable management strategies can improve the ability of tropical forest ecosystems to adapt to climate change (*high confidence)*, and the benefits of adaptation interventions often outweigh the costs (*medium confidence*). Adaptation of tropical forests to climate change provides an opportunity for tropical countries to develop forest policies that create incentives for environmental services such as carbon storage and biodiversity refugia. Forest restoration using a diverse mix of native species can help rebuild the climate resilience of tropical forests, but is best implemented alongside other sustainable forest management strategies and adaptation interventions (*high confidence*) {CCP7.5; Box CCP7.1}

Community-based adaptation, built on Indigenous Knowledge (IK) and Local Knowledge (LK) over centuries or millennia, is often identified as an effective adaptation strategy to climate change (*high confidence*). For successful adaptation of tropical forest communities, it is vital to consider IK and LK in addition to modern scientific approaches, together with consideration of non-climatic vulnerabilities (e.g., poverty, gender inequality and power asymmetries) (*high confidence*) Climate change vulnerability and adaptive capacity have a historical and geopolitical context, conditioned by value systems and development models. Transformative and sustainable practices are required for effective management of tropical forests (*high confidence*) {CCP7.4; Box CCP7.1}

Building resilience of tropical forests to climate change relies on adaptation in combination with reduction of direct and underlying drivers of deforestation and forest degradation (*high confidence*). Tropical deforestation is largely driven by agriculture, both from subsistence farming and industrial agriculture (e.g., oil palm, timber plantations, soybeans, livestock) (*high confidence*). While poverty and population growth combined with poor governance fuel subsistence agriculture (*high confidence*), industrial agriculture is often driven by international market forces for commodities and large-scale land acquisitions (*high confidence*). {CCP7.2.3}

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

Governance responses to addressing the direct and underlying drivers of deforestation have been inadequate to reduce pressures, yet the complexity of tackling drivers of forest loss and degradation is increasing as climate impacts on forests and ecosystems increase (*high confidence*). Transformative levers towards improving environmental governance and resilience of tropical forests include: incentivizing and building capacity for environmental responsibility and discontinuing harmful subsidies and disincentives; reforming segmented decision-making to promote integration across sectors and jurisdictions; pursuing pre-emptive and precautionary actions; managing for resilient social and ecological systems in the face of uncertainty and complexity; strengthening environmental laws and policies and their implementation; acknowledging land tenure and rights; and inclusive stakeholder participation (*medium confidence*). {CCP7.6}

CCP7.1 Introduction

Climate change is already impacting tropical forests around the world, including through distributional shifts of forest biomes, changes in species composition, biomass, pests and diseases and increase in forest fires (*high confidence*). These impacts are often compounded by non-climatic factors such as conversion of land for other uses, burning to clear land, mining, and road and infrastructure development. It is notable that, despite societal awareness and financial opportunities to restore forests (Brancalion and Chazdon 2017), tropical forests are increasingly threatened. For instance, the conversion of tropical forests to large-scale agricultural production (mainly soybeans, oil palm, maize, cotton, livestock), is amongst the strongest drivers of species richness decline of both flora and fauna, thereby impacting the adaptation opportunities of ecosystems and local people to climate change (IPBES 2018). Reducing direct and indirect drivers of deforestation and forest degradation is therefore critical to building, maintaining or enhancing the resilience of tropical forests against climate and non-climate drivers alike (*high confidence*).

With climate change-related drivers becoming increasingly important in the future, changes to tropical forests will most *likely*[2] be aggravated overall, although some tropical forests may temporarily benefit, physiologically, from higher temperatures and changes in precipitation patterns. To the degree to which forests are affected by climate change and other drivers, their resilience against these stressors is diminishing leading to a reduction in the regulating, supporting, provisioning and cultural ecosystem services they provide (Alroy 2017; Cadman et al. 2017; Pörtner et al. 2021) (Chapter 2) (*high confidence*). This, in turn, is affecting the lives and livelihoods of millions of people who depend on forests and their products, in particular forest dwelling communities, but also, via the teleconnections between forests and surrounding areas of influence, in socio-ecological systems outside the forests themselves.

While strong mitigation efforts are fundamental to minimizing future climate impacts on forests, forest management can be improved in many places in support of enhancing the resilience of tropical forests, often with significant co-benefits for carbon storage, biodiversity, food security and ecosystem services (*high confidence*). Sustainable management practices allow forests to be utilized, frequently with equally high or even higher productivity levels, while keeping their core functions intact. While there are numerous approaches to managing forests and forest landscapes sustainably, an element that appears to be critical are property rights and tenure arrangements allowing stewards of the land, including Indigenous Peoples, securing long-term access and utilization of forest resources *(medium confidence)* (Rahman and Alam 2016 and Naughton-Treves 2014).

The interconnections of climate risks and non-climate drivers facing tropical forests, their impacts on rates and extent of deforestation and forest degradation, loss of ecosystem services and biodiversity, leading to unsecured human well-being, contrasts with the sustainable forest management on protecting forest ecosystems and enhancing their resilience against these drivers are framed in Figure CCP7.1. The conceptual framework not only illustrates the complexity and scale of the challenge, but also provides opportunities to mitigate impacts at different scales, whereas eliminating the underlying drivers, both climate and non-climate related, must be the goal of policies and measures at global, national and subnational levels, involving state and non-state actors alike.

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range.

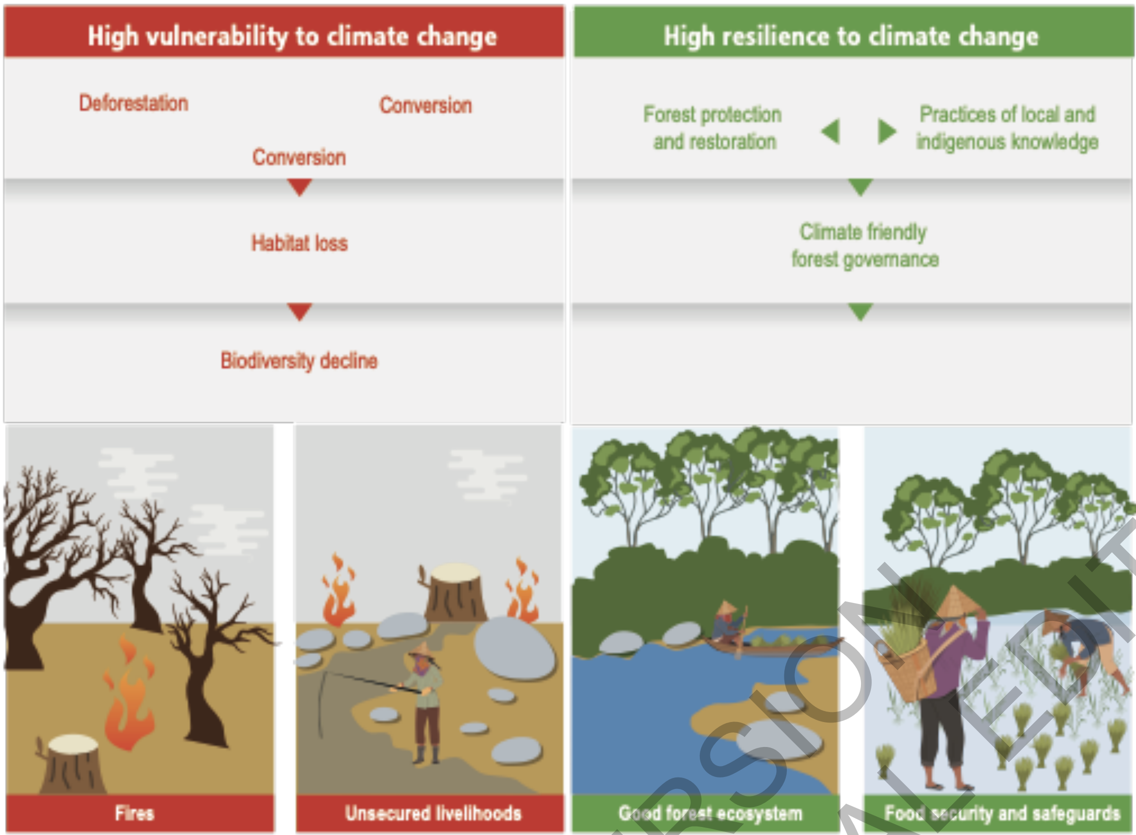

Figure CCP7.1: Impacts of climate change and human disturbances on tropical forests lead to high risk of biodiversity loss and uncertainty of livelihoods for the majority of forest dependent communities (left side). Good forest governance would increase the resilience of tropical forest through better adaptation and mitigation to climate change (right side)

Building on what has been presented in IPCC AR5, SR15, and SRCCL, section 7.2 of this Cross-Chapter Paper first briefly describes the types and extent of tropical forest ecosystems and then looks at current rates and drivers of deforestation and forest degradation. Section 7.3 presents current and projected climate change impacts on tropical trees and forests, focusing primarily on drought, heat and fires, looking from physiological responses to risks, projected climate change impact, and forest resilience. Section 7.4 addresses the impacts of climate change and tropical forest destruction on the livelihoods and well-being of communities and peoples living in or being strongly dependent upon tropical forests. This section includes a Box on Indigenous Knowledge and Local Knowledge and Community-based Adaptation. Section 7.5 assesses adaptation options for the sustainable management of tropical forests drawing upon the protection, management and restoration framework, and includes a Box on the connection between sustainable forest management and the United Nations Sustainable Development Goals. Section 7.6, finally, assesses opportunities and challenges of tropical forest governance to maintain and enhance resilience against climate change impacts on forests.

CCP7.2 The Current State of Tropical Forests

In the most recent Global Ecological Zones map produced by the Food and Agriculture Organization (FAO) for the year 2010, tropical vegetation has been defined as encompassing regions which are frost-free during all months in the year (FAO 2012). Further, the tropical vegetation has been sub-classified into tropical rainforest, tropical moist forest, tropical dry forest, tropical shrubland, tropical desert, and tropical mountain systems based on climate in combination with vegetation physiognomy and orographic zone (Table SMCCP7.1). IPCC has used the basic FAO classification in its National Greenhouse Gas Inventories Guidelines (IPCC 2019).

Since the FAO ecological zones represent potential biome extents, the present area under forest is assessed using the European Space Agency Climate Change Initiative Land Cover dataset (ESA 2017). The ESA dataset provides a direct mapping to IPCC land categories (e.g., "forest"), allowing for standardized and consistent reporting of existing forest and forest gain/loss in each ecological zone. The most extensive tropical ecological zone is the tropical rainforest (1,459 Mha or about 25% of all tropical ecological zones), followed by tropical desert (which is not further considered here), tropical moist forest, tropical shrubland, tropical dry forest and tropical mountain system (Table CCP7.1; Figure CCP7.2). Mangroves are not explicitly considered in the FAO classification. Tropical rainforest occurs largely in South America, Africa, and South and South East Asia, and is the most intact tropical forest biome (Table CCP7.1). Significant portions of tropical moist forest, which abuts tropical rainforest in many regions but experience a longer dry season, have been lost in most regions (Table CCP7.2). Tropical moist forest typically grades into the highly-threatened tropical dry forest ecological zone, of which only about a third exists under forest cover at present. Only about 44% of tropical mountain systems, which occur approximately above 1000 m above mean sea level, are presently under forest cover. While the FAO classification provides the potential tropical ecological zones (roughly, "vegetation types"), there are large differences in the extents of global tropical forest biomes which are still remaining as reported by different sources (Sayre et al. 2020; Ocón et al. 2021). These differences result from differences in biome definition, data source, the definition of "forest," and the method used for classifying remotely-sensed data. For example, the reported global area of tropical dry forests ranges from 105 Mha to 645 Mha (Pan et al. 2013; Bastin et al. 2017; Ocón et al. 2021).

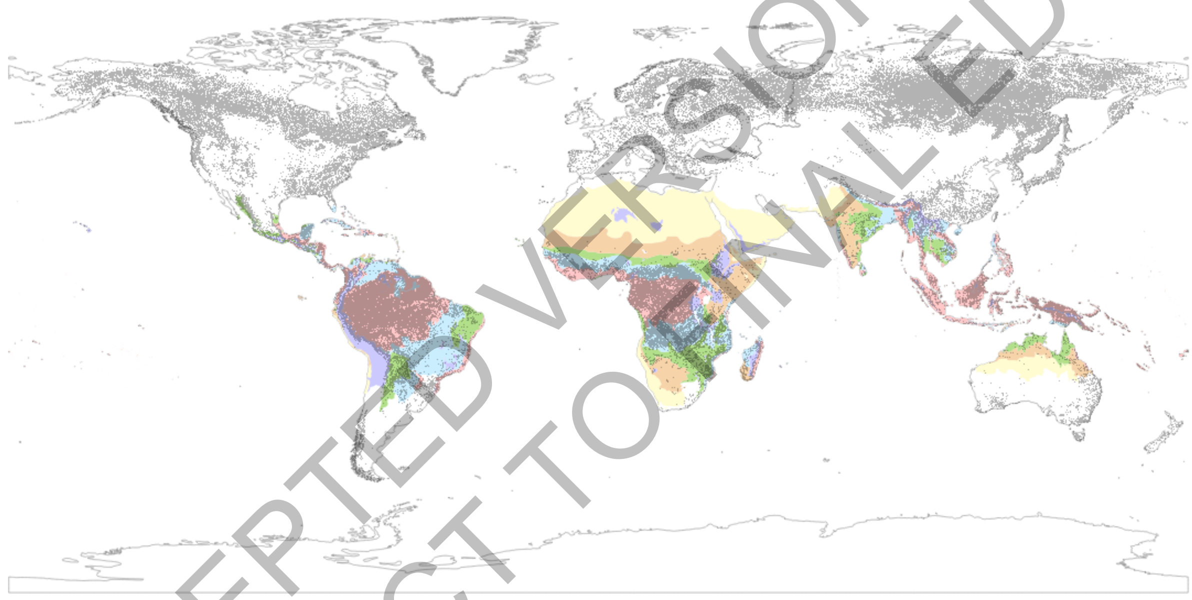

Figure CCP7.2: Colours represent tropical ecological zones as defined by the FAO (FAO 2012) Areas classified as "Forest" in the 2020 ESA Land Cover CCI Product (ESA 2017) are overlaid in grey.

Table CCP7.1: Areas in tropical ecological zones as defined by the FAO (FAO 2012). [1]Existing forest represents areas classified as "Forest" in the 2020 ESA Land Cover CCI Product (ESA 2017). All units are in million hectares, except where indicated.

Ecological zone	Africa	South America	North America	Asia	Australia	Oceania	**Global**	**Existing forest**[1]	**Existing forest (%)**[1]
Tropical rainforest	399	659	48	323	3	13	**1459**	**1140**	**78.2**
Tropical moist forest	464	428	43	139	0	0	**1077**	**509**	**47.3**
Tropical dry forest	366	167	39	143	67	0	**784**	**236**	**30.0**

Tropical shrubland	595	11	0	116	85	0	**808**	**60**	**7.4**
Tropical desert	871	13	0	269	141	0	**1296**	**6**	**0.4**
Tropical mountain system	147	188	16	90	0	2	**443**	**194**	**43.9**

CCP7.2.1 Distribution and Biodiversity of Tropical Forest Ecosystems

Tropical forests are indisputably the areas with highest biological diversity on Earth, both in absolute and density (species per area) terms (Plotkin et al. 2000). Estimates account that tropical forests harbor half or even more of world's biodiversity (Kier et al. 2009; Jenkins et al. 2013), even though this figure is highly uncertain owing to varying estimates of undescribed species (Mora et al. 2011). For example, it is estimated that there are at least 40,000, but possibly more than 53,000 tree species in tropical forests (Slik et al. 2015). A vast majority of this biodiversity and Indigenous Knowledge and Local Knowledge associated with its use remains poorly explored, presenting a vast unlocked genetic reserve at risk of loss, although many of today's important medicines, foods, and ecosystem products originate from tropical forests (Kouznetsov and Amado Torres 2008; Calderon et al. 2009), staple foods (Brondízio 2008; Isendahl 2011) (Maia and Mourão 2016).

Rates of global biodiversity loss in the past few decades have accelerated to levels that are, for some taxa, approaching the estimated rate of 75% of taxa extinction found in Earth's "big five" mass extinction events (Barnosky et al. 2011) (Díaz et al. 2019) (Davison *et al*., 2021). Even though species-area relationships tend to overestimate extinction rates (He and Hubbell 2011). , there is evidence that species richness in tropical forests is alarmingly approaching or surpassing the taxa extinction value in this period (45% for dung beetles, 51% for lizards, 65% for ants, and 80% for mammals) should deforestation and habitat loss continue at the current pace (Alroy 2017) (Ceballos et al. 2017). Moreover, there is reasonable understanding that these numbers are underestimated and, as such, tropical forest loss and degradation alone will precipitate a sixth mass extinction event (Giam 2017). A total of 13 out of the 25 global biodiversity hotspots for conservation are located in tropical forests, such as Brazil's Atlantic Forest and India's Western Ghats/Sri Lanka (Myers et al. 2000). While forest loss and degradation have been the main cause of tropical biodiversity loss in the past, climate change now arises as a major threat not only for individual tropical forest species or taxa – as already observed for frogs (Pounds et al. 2006) - but for whole communities (Esquivel-Muelbert et al. 2019), and even entire tropical forest ecoregions (Lapola et al. 2018).

CCP7.2.2 Rates of Deforestation, Tropical Reforestation and Connections to Climate Resilience of Tropical Forests

More than 420 million ha of forest were lost globally in the 1990-2020 period due to deforestation, and more than 90% of that loss took place in tropical areas (FAO 2020). For the 2015-2020 period, the tropical deforestation rate decreased compared to 2010-2015, being estimated at 10.2 Mha yr-1 (FAO 2020). But reforestation and afforestation rates have also decreased, resulting in a tropical forests net loss rate of 7.3 Mha yr-1 in the 2015-2020 period. Overall, the net loss rate has slightly decreased (-4%) since 1990 (*high confidence*). However, a particularly high upward trend is observed in Central America and the Caribbean while a small increase (2%) is observed in the tropical zone of Africa, during the periods from 2010-2015 to 2015-2020 (see Table CPP7.2).

Table CCP7.2: Trends in net tropical forest loss, reforestation and expansion rates (1000 ha yr-1) from 2010-2015 to 2015-2020 periods by regions.

Región	Net loss rate 2010-2015	Net loss rate 2015-2020	Net loss rate Observed Trend	Reforestation rate 2010-2015	Reforestation rate 2015-2020	Reforestation rate Observed Trend	Forest expansion rate 2010-2015	Forest expansion rate 2015-2020	Forest expansion rate Observed Trend
Africa	3911.37	3982.97	Increase (0-25)	406.82	297.55	Decrease (25-50)	442.89	390.47	Decrease (0-25)
Asia and Oceania	1083.02	780.49	Decrease (25-50)	627.46	582.06	Decrease (0-25)	1227.15	1130.38	Decrease (0-25)
Central America and Caribbean	59.4	122.45	Increase (>50)	51.36	44.51	Decrease (0-25)	104.74	41.34	Decrease (25-50)
South America	2663.96	2498.65	Decrease (0-25)	1081.9	846.24	Decrease (0-25)	447.88	297.19	Decrease (25-50)
Total	7717.76	7384.57	Decrease (0-25)	2167.49	1770.36	Decrease (0-25)	2222.66	1859.38	Decrease (0-25)

Trend direction: Increase, Decrease

Magnitude of trend (%): 0-25, 25-50, >50

Table Notes:
Details on the Table CCP7.2 elaboration are provided in the Supplementary Material (SMCCP7.1)

CCP7.2.3 Drivers of Deforestation and Forest Degradation

Deforestation and forest degradation both affect carbon stocks, biodiversity loss and the provision of ecosystem services, leading to a reduction in resilience to climate change and exacerbating forest landscape vulnerability even in the absence of direct anthropogenic action (*high confidence*) (Barlow et al. 2016; Aleixo et al. 2019; X. Feng et al. 2021; Saatchi et al. 2021). There is also clear evidence of deforestation influencing temperatures and the hydrological cycle at local to regional scales resulting in reduced precipitation and evaporation and increased runoff relative to unaffected areas (*high confidence*) [CCP7.3.6] (Jia et al. 2019; Douville et al. 2021). Negative trends in biodiversity and ecosystems are predicted to undermine 80% of the Sustainable Development Goals targets related to poverty, hunger, health, water, cities, climate, oceans and land(IPBES 2019). Therefore, besides GHG mitigation, reducing the driving forces leading to deforestation and forest degradation is of the utmost importance for forest resilience, biodiversity protection, avoiding regional climatic changes and the provision of critical ecosystem services, and communities whose livelihoods depend on forests (*high confidence*) (Curtis et al. 2018; IPBES 2019; Jia et al. 2019; Seymour and Harris 2019; Pörtner et al. 2021; Saatchi et al. 2021).

Drivers of deforestation and forest degradation can be distinguished between proximate (i.e. direct) and underlying (i.e. indirect). Direct drivers, such as agriculture (including crops, livestock and plantation forestry), infrastructure development (which often provides access to intact forests and catalyzes deforestation), or timber extraction, are place-based and visible. They are influenced by underlying driving forces, such as demographic, economic, technological, political and institutional, or cultural factors, which typically form complex interactions and act at multiple scales, frequently without any direct connection to the areas of forest loss (Geist and Lambin 2002).

Agriculture is by far the largest direct driver of tropical deforestation, with great differences between commercial and subsistence farming and large variation across regions (Figure CCP7.3). Over 80% of tropical deforestation between 2000 and 2010 was caused by agriculture, proportionally ranging from ca. 75% in Africa and Asia to ca. 95% in the Americas (FAO and UNEP 2020), but both the scale of deforestation and the relative contribution of different drivers have changed considerably over time (*high confidence*) (Hosonuma et al. 2012; Curtis et al. 2018; Seymour and Harris 2019; FAO and UNEP 2020).

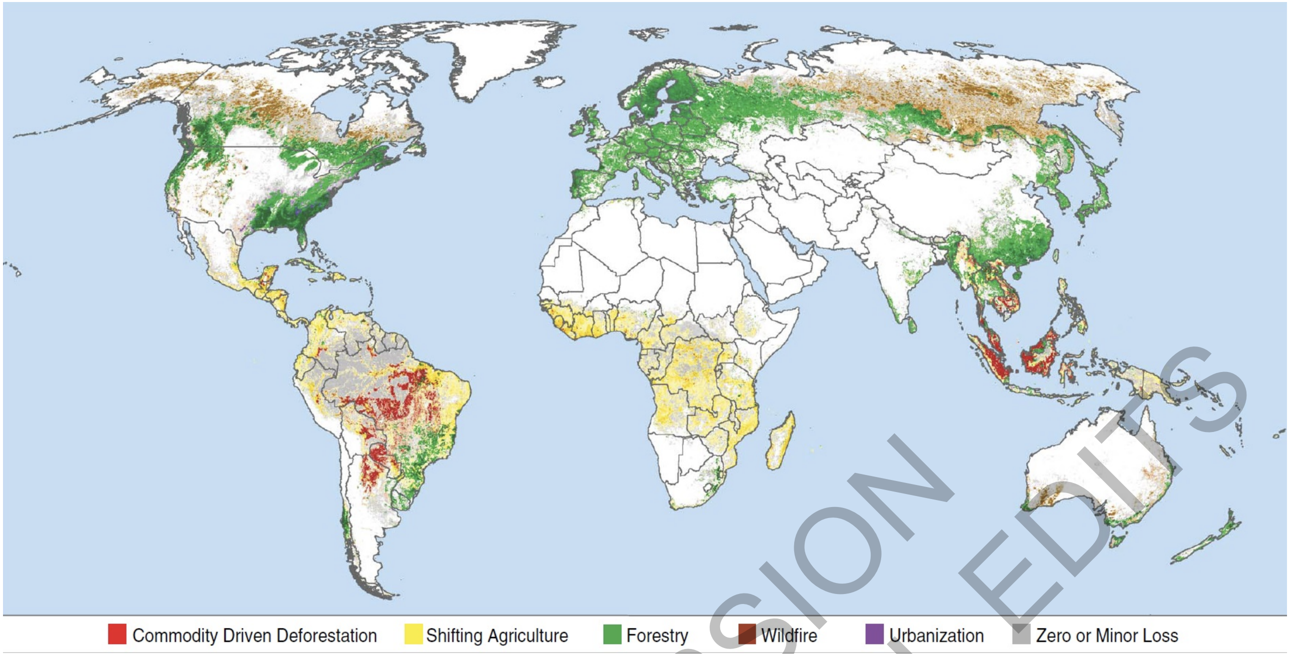

Figure CCP7.3: Primary drivers of forest cover loss for the period 2001 to 2015. Darker color intensity indicates greater total quantity of forest cover loss. While some tropical forest cover loss is temporary, a large portion is related to deforestation. Source: (Curtis et al. 2018). Reprinted with permission from AAAS.

Forest degradation is more difficult to track, but can have large negative effects on carbon storage, provision of ecosystem services, and biodiversity (B. W. Griscom et al. 2017; Houghton and Nassikas 2017). A recent analysis suggests that forest degradation is increasing and is now surpassing deforestation rates in the Brazilian Amazon (Aparecido Trondoli Matricardi et al. 2020). As with deforestation, drivers of forest degradation differ by region, such that timber extraction was by far the most important degradation driver in Latin America and Asia, whereas in Africa wood fuel consumption contributed to about half of forest degradation between 2000 and 2010 (Hosonuma et al. 2012).

Though not as visible as direct drivers, indirect or underlying causes can greatly influence direct drivers, and must be addressed to reduce pressures on forests (*high confidence*) (e.g. FAO 2016b; Fehlenberg et al. 2017; Pendrill et al. 2019b; Bos et al. 2020; Junquera et al. 2020; Ken et al. 2020; Kissinger 2020; Siqueira-Gay et al. 2020; Hoang and Kanemoto 2021). Next to population growth, poverty and insecure land tenure (Ariti et al. 2015; Arevalo 2016; FAO 2016a; Ken et al. 2020; Siqueira-Gay et al. 2020; Verma et al. 2021), many developing tropical countries identify weak forest sector governance and institutions, lack of cross-sectoral coordination, and illegal activity (related to weak enforcement) as critical underlying drivers (FAO 2016a; Ken et al. 2020; Kissinger 2020) [CCP7.6].

International and market forces, particularly commodity markets and, increasingly, large-scale land acquisitions are also key underlying drivers (*high confidence*) (Assunção et al. 2015; Henders et al. 2015; Conigliani et al. 2018; Ingalls et al. 2018; Garrett et al. 2019; Pendrill et al. 2019b; Kissinger 2020; Neef 2020; Hoang and Kanemoto 2021) [WG2 Chapter 5.13]. Deforestation related to commodity imports is increasing, illustrating the growing influence of global markets in deforestation dynamics (Henders et al. 2015). Although some of this production is consumed domestically, 29–39% of deforestation was driven by international trade, primarily from Europe, China, the Middle East and North America (Pendrill et al. 2019a). While many developed countries, China and India have achieved net domestic forest gains, their consumption patterns have increased deforestation embodied in their imports to varying degrees, frequently from biodiversity hotspots (Hoang and Kanemoto 2021). Fifty percent (50%) of the biodiversity loss associated with consumption in developed economies occurs outside their territorial boundaries (Wilting et al. 2017). The increasing prominence of medium- and large-scale clearings of forest between 2000–2012, particularly in Southeast Asia and South America suggests the growing need for policy interventions targeting industrial-scale agricultural commodity producers (Austin et al. 2017). However, countries have been slow to address underlying drivers such as international demand for agricultural commodities. A review of 43 countries' REDD+ readiness documents found that proposed policy interventions largely missed the agricultural drivers identified (Salvini et al. 2014). An assessment of policy responses to rubber and coffee production highlights the challenges governments face in identifying correlations between the direct drivers and related underlying drivers, with international drivers being the most challenging to address (Kissinger 2020).

CCP7.3 Current and Projected Climate Change Impacts on Tropical Forests (Drought, Temperature, Extreme Events)

While early dynamic global vegetation models predicted biome shifts and contractions of tropical forests, more recent efforts have focused on biome changes at more regional scales, or on functional aspects of tropical forests, such as plant physiological and phenological changes, drought-related mortality, population dynamics, interspecies interactions and community responses, ecohydrology, risk of fire and related impacts, soil nutrient and microbe-plant interactions. Climate change is expected to increase temperatures across the tropics, with attendant variability in rainfall, and more extreme events such as intense storms, droughts and wildfires (Zelazowski et al. 2011; Malhi et al. 2014; Brando et al. 2019). This could be expected to have structural and functional impacts on tropical forest biomes (Malhi et al. 2014; Adams et al. 2017). This section looks at responses of tropical trees and forests to current and future climate-change related pressures, focusing on physiological responses including growth, mortality and regeneration, fire risk, and ecological vulnerability, as well as on climate effects of tropical forest loss.

CCP7.3.1 Tropical Tree Physiological Responses to Climate Change

With rising temperatures and atmospheric carbon dioxide, possibly accompanied by greater variability in soil moisture availability, a key question is how tropical forest trees respond physiologically (especially photosynthesis and respiration which determine net growth rates) and how well they can acclimate (i.e., able to adapt) to climate change (Dusenge et al. 2019). Key climate factors influencing tree growth on pan-tropical forests are precipitation, solar radiation, temperature amplitude and relative soil moisture (Wagner et al. 2014).

The temperature response of photosynthetic carbon uptake in tropical trees seems remarkably similar across moist and dry forest types as well as for light-demanding, fast-growing species compared to shade-tolerant, slow-growing species (Slot and Winter 2017). It is generally agreed that photosynthesis in tropical species can acclimate to moderate levels of warming but beyond this there would be no net gain in carbon (Slot and Winter 2017). The factor that limits photosynthesis in different tropical forests will depend on water-availability. In water-limited dry forests, photosynthesis may decline largely due to stomatal closure, while in wet forests, the decline may largely be driven by warming-related changes to leaf biochemistry (Slot and Winter 2017). A recent modelling approach suggests that the limits of photosynthetic thermal acclimation may be an increase of about 2˚C, in terms of maximum tolerated temperature, with enhanced tree mortality beyond this level of warming (Sterck et al. 2016).

A critical concern for plant function has been that higher temperatures will enhance respiration rates, potentially resulting in tropical forests becoming net carbon sources (rather than photosynthesis driven carbon sinks) (Gatti et al. 2021). Some studies suggest that excessive respiration is less of a concern as respiration rates can acclimate to elevated temperatures over time (Lombardozzi et al. 2015; Pau et al. 2018). Thermal acclimation of respiration has been shown in a seasonally dry neotropical forest (Slot et al. 2014), while models indicate that increases in plant respiration could halve by the end of the 21st century through acclimation, thereby partly ameliorating the potential release of carbon from tropical forests (Vanderwel et al. 2015). A contrary view is that plant physiological processes, such as the photosynthesis in tropical canopy trees, are already functioning at levels close to or beyond their thermal optimum limits and that any further temperature increase would turn them from a sink into a carbon source (Mau et al. 2018)
One of the most pressing questions regarding forest responses to increasing atmospheric CO_2 levels is whether trees experience enhanced growth rates as a result of the so-called CO_2 fertilization effect [Box 2.3

in IPCC SRCCL]. Observed changes in the terrestrial carbon sink and process-based vegetation models indicate that tropical vegetation response to CO2 fertilization (Schimel et al. 2015) is combined to other factors such as nitrogen deposition and length of the growing season, while aerosol-induced cooling may also have played a role in enhancing carbon sink [Box 2.3 in IPCC SRCCL]. Contrastingly, evidence for CO2 fertilization of growth in individual tropical tree species is generally lacking or controversial (Silva and Anand 2013), or not as substantial as expected (Sampaio et al. 2021). It is however widely agreed that the intrinsic water-use efficiency of a tree, i.e. the amount of carbon assimilated as biomass per unit of water used, increases under elevated atmospheric CO2 levels due to the regulation of stomata (cells on the leaf surface which regulate the exchange of water and gases between the plant and the atmosphere) (Van Der Sleen et al. 2015; Bartlett et al. 2016; Rahman and Alam 2016; Keeling et al. 2017). Tropical dry forests (c. 1000mm annual rainfall) exhibit changes in water-use efficiency (WUE), relative to CO2, at least twice as much as do tropical moist forests (c. 4000mm rainfall) (Adams et al. 2019).

Other key components in the forest system are plant-microbe-soil nutrient interactions, which play major roles in carbon cycling and plant photosynthetic response to increased atmospheric CO_2 and warming (Zhang et al. 2014; Singh and Singh 2015; Du et al. 2019). Phosphorus is generally a limiting factor in tropical forest soils though this may be species-specific (Ellsworth et al. 2017; Turner et al. 2018). Mycorrhizal fungi (both arbuscular and ectomycorrhizal) play major roles in water acquisition of host plant and their responses to drought in dry tropical forest (Lehto and Zwiazek 2011) as well as in the capture and transfer of nutrients, especially N (which may otherwise become limiting), to host plants. Climate change factors can thus be expected to alter the nature of soil-plant interactions with consequences for the species composition and biodiversity of tropical ecosystems (Pugnaire Francisco et al. ; Terrer et al. 2019)

CCP7.3.2 Climate-Related Mortality and Regeneration in Tropical Forests

Drought-related mortality of tropical trees shows complex patterns which could change forest community structure and composition with cascading effects on biodiversity (McDowell et al. 2020). During drought, the mortality rate is enhanced in larger-sized trees in tropical forests (as is the case with all forests globally) with significant impacts on forest structure, carbon storage and regional hydrology (Bennett et al. 2015). The mortality rate of neotropical moist forest trees appears to be consistently increasing since the 1980s (McDowell et al. 2020) with plant functional types such as softwood, pioneer and evergreen species suffering higher mortality during years of extreme drought (Aleixo et al. 2019). Large trees (>30 cm dbh) in tropical dry forests have much lower mortality rates than those reported for tropical moist forests (Suresh et al. 2010). Contrary to expectation, during prolonged droughts in these dry forests, deeper-rooted tree species are more *likely* to die than shallow-rooted ones, which are more adapted to changes in soil moisture content, because of water depletion in the deepest unsaturated zone (Chitra-Tarak et al. 2018).

Regeneration of tropical tree seedlings and their response to a changing climate is inadequately understood. Experimental work suggests that tropical moist forest tree seedlings and saplings can acclimate photosynthetically to moderate levels of warming and, unlike adults, may even exhibit increased growth rates (Cheesman and Winter 2013; Slot and Winter 2018) Some moist forest seedlings also show plasticity to recurrent drought episodes by enhancing their growth rates when favorable moisture conditions return, while others fail to respond (O'Brien et al. 2017). The nature of response also seems to be mediated by neighborhood diversity, with greater plasticity in more diverse communities (O'Brien et al. 2017). Seedlings in tropical dry forests subject to burning show enhanced growth rates post-fire and within two years attain similar height of seedlings in unburnt areas (Pulla et al. 2015), though the environmental drivers of seedling growth post-fire are not well understood (Bhadouria et al. 2017).

The net outcome of the population dynamics processes of growth, mortality and regeneration is change in species composition as a consequence of a changing climate. In the Amazon forests, dry habitat-affiliated genera have become more abundant among the newly recruited trees, while the mortality of moist habitat-affiliated genera has increased at places where the dry season has intensified most, thus driving a slow shift towards a drier forest type (Esquivel-Muelbert et al. 2019). A similar multi-decadal shift in West-African forest species composition towards more dry-affiliated species as a response to long-term drying has been recorded (Aguirre-Gutiérrez et al. 2020). While upward shifts in the tree line and in the range of individual tree species have been recorded at several temperate mountain regions, evidence from the tropics is rare. A large-scale study from 200 plot inventories of >2000 tree species across a ~3000m elevation gradient in the

Andean tropics and sub-tropics has shown that the relative abundances of tree species from lower, warmer locations were increasing at these sites indicating that "thermophilization of vegetation" (increased domination of plant species from warmer locations) was indeed taking place as expected (Fadrique et al. 2018) [Section 2.5.4.2.1 in Chapter 2].

CCP7.3.3 Fire Risks from Climate Change in Tropical Forests

Temperature rise and prolonged droughts increase the danger of fires in drained peatlands and tropical forests in South East Asia and the Amazon (da Silva et al. 2018; Pan et al. 2018; Sullivan Martin et al. 2020), resulting in large carbon emissions, which reached 11.3 Tg CO_2 per day during September-October 2015 (Huijnen et al. 2016; Yin et al. 2020) and changes in forest composition and biodiversity (Asner et al. 2000; Hoffmann et al. 2003) *(high confidence*). In many cases, tree mortality due to fire is poorly recorded in the literature, but the available data suggests that fire-induced mortality has increased in recent years (Figure CCP7.2) (Malhi et al. 2014; Brando et al. 2019) *(high confidence*). While large forest and peat fires used to be associated mainly with El Niño Southern Oscillation (ENSO) events, there is now evidence that tropical rainforests in Indonesia may experience higher fire danger from increased temperatures even during non-drought years due to high evaporation rates of fragmented forests (Fernandes et al. 2017; McAlpine et al. 2018). The droughts of 2007 and 2010 in the Amazonian region caused 12% and 5% of the southeastern Amazon forests to burn, respectively, as compared to <1% of these forests burning during non-drought years (Brando et al. 2014; da Silva Júnior et al. 2019; Pontes-Lopes et al. 2021). Moreover, degraded forests in Ghana are more vulnerable to fires during droughts (Dwomoh et al. 2019).

Factors other than solely climate also interact in enhancing the danger of tropical forest fires. For instance, the extent of burned area of rainforests in Borneo has shown that subsurface hydrology, (i.e., hydrological drought), interacts with meteorological drought and, hence, fires have become more intense in recent decades following the progressive desiccation of the island over the past century (Taufik et al. 2017). Bornean forest fire risk also increased through the interaction of drought with land use conversion for logging, oil palm and tree plantations, and human settlements (Sloan et al. 2017). Similarly, simulations of future fire risks in the Amazon show that extensive land use change under the RCP 8.5 scenario results in 4 to 28-fold enhanced area of forest burned by fire by 2080-2100, as compared to 1990-2010, whereas on a RCP 4.5 scenario the area burned would be enhanced by 0.9 to 5.4-fold (Le Page et al. 2017).

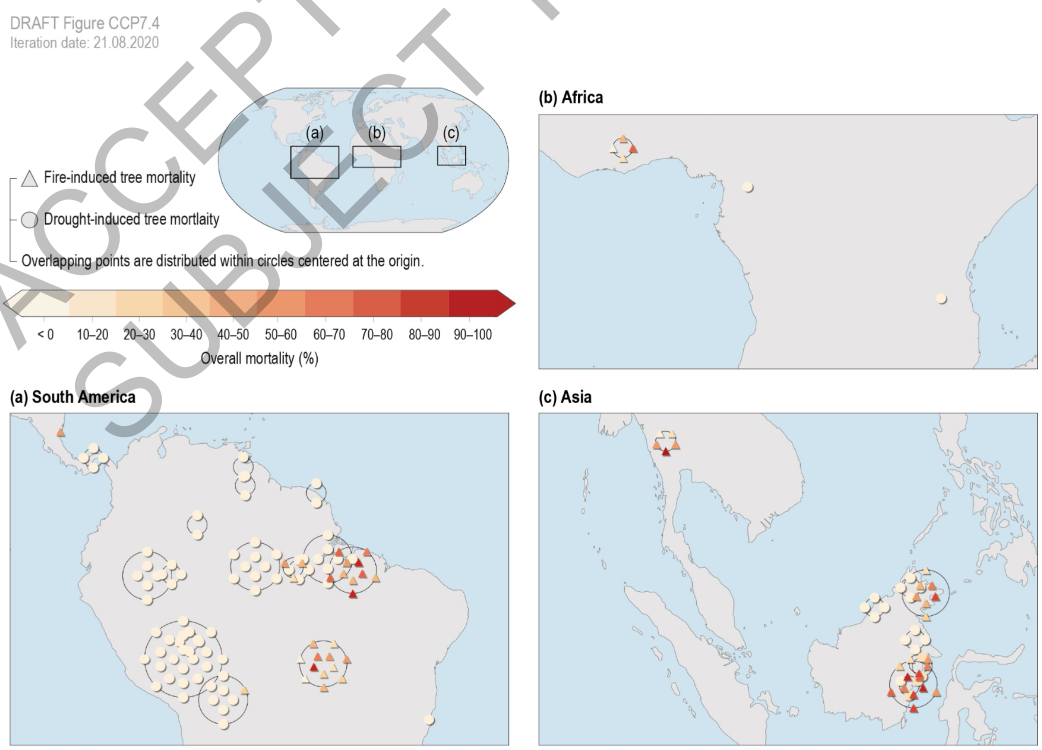

Figure CCP7.4: Documented instances of tree mortality in tropical moist forests due to fire (1992-2016) and drought (1982-2005). These occurrences were associated with anomalies in precipitation and temperature over the study period. Adapted from (Brando et al. 2019).

CCP7.3.4 Current climate risks for tropical forests

Impacts of climate change on tropical forest cover seem to correlate with climatic zone. Natural selection of drought tolerant species is observed in tropical dry forests under a prolonged water deficit environment (Stan and Sanchez-Azofeifa 2019). Tropical montane forests are highly sensitive to warming and associated changes in cloud cover and moisture, with evidence that such forests are already being impacted through "browning" (loss of biomass) from increased warming since the 1990s (Krishnaswamy et al. 2014).

Besides higher temperatures, current climate risks also depend on regional responses to a variety of climate events. For example, tropical biomes across the three continents may respond differently to ENSO events in terms of carbon fluxes and balance. During the 2015-2016 ENSO event, different processes were dominant for the carbon fluxes anomaly in the tropical regions. In Asian forests this anomaly was primarily derived from enhanced fire occurrence, in African forests through increased ecosystem respiration (from higher temperatures), and in South American forests by ecophysiological effects, through the gross primary production (GPP) expressed as reduced carbon uptake (Liu et al. 2017; van Schaik et al. 2018). It has also been shown that the probability of drought spells at the beginning and end of the rainy season is higher in the areas with the highest deforestation (Leite-Filho et al. 2019). Furthermore, it has been observed that Amazon rainforest resilience is being lost faster in regions with less rainfall and in parts of the rainforest that are closer to human activity (IPCC 2014; Seiler et al. 2015) (CCP7.3.6). Conversely, it has been pointed out, on the basis of vegetation indices, that temperature has a greater influence on resilience than does precipitation, and tropical forests are more resilient to climate change when they are more diverse (Feng et al. 2021) (CCP7.3.6).

Biomes such as seasonally dry tropical forests subject to higher variability in rainfall or other climatic factors may be more resilient to fire and drought (Pulla et al. 2015; Liu et al. 2017), though there could be changes in species distributions as a result of disturbances (Allen et al. 2017). A regime of long-term, high rainfall variability seems to be critical in determining the overall resilience of tropical forests and savannas to climate disturbances (Ciemer et al. 2019), highlighting the heterogeneity of the tropical landscape to climate risk. Similarly, forest composition, nutrient limitations, and biodiversity can influence forest resilience to disturbances. Recent evidence suggests that the degree of forest disturbance also affects the mechanisms through which biodiversity influences forest functioning (Schmitt et al. 2020). Neotropical secondary forests also showed high resilience by maintaining their biomass through high productivity and rates of recovery following major disturbances (Poorter et al. 2016). However, the possibility of tropical forests reaching "tipping points" in their resilience and experiencing rapid die-off cannot be ruled out (Verbesselt et al. 2016).

CCP7.3.5 Projected Impacts of Climate Change on Tropical Forest

Climate change projections indicate increased warming and changes in rainfall patterns in the tropical region as elsewhere globally (IPCC AR6 WG1). These would have impacts on carbon stocks (Mitchard 2018; Hubau et al. 2020), water availability (Tamoffo et al. 2019), and structure and diversity (Malhi et al. 2014; McDowell et al. 2020) in tropical forests, amplified by deforestation (CCP7.3.6).

Tropical forests are critical repositories of global carbon; living tropical trees are estimated to hold 200-300 Pg C or about one-third of the levels in the atmosphere (Mitchard 2018). CMIP5 and CMIP6 Earth System Models (ESM) project an increasing future tropical carbon sink, which is particularly strong in the scenarios with more pronounced increase in atmospheric CO2 concentration (Koch et al. 2021). However, major uncertainties regarding the ecophysiological processes governing carbon turnover and tree mortality under a changing climate (Hartmann et al. 2015; Pugh et al. 2020), and the ecosystem-level responses of tropical forests to elevated atmospheric CO2 (Körner 2009) explain the contrast between observational data and modeling results (Rammig and Lapola 2021). Observational data show that structurally intact old-growth tropical forests have been net sinks of atmospheric carbon in recent decades, but there is evidence that the capacity of such intact tropical forests to build up carbon stock may be limited as biomass peaked during the 1990s and has since weakened by 30% in the Amazon since the 1990s (high confidence), mainly due to increased tree mortality and faster carbon turnover, and the African tropical forest sink following this trend since about 2010 (Hubau et al. 2020; Gatti et al. 2021). From a peak pan-tropical (Amazonia, Africa and Southeast Asia) forest sink of 1.26 Pg C yr-1 during the 1990s, it is projected to decline to an uptake of only 0.29 Pg C yr-1, reaching zero, in the Amazon, during the 2030s (Hubau et al. 2020). This decline will possibly be driven by the reduced rates of forest carbon uptake from the weakening global CO2 fertilization effect mediated by limiting soil nutrient, and reduced water availability and higher temperatures during extreme droughts (Qie et al. 2017; Fleischer et al. 2019; Wang et al. 2020), reinforced by deforestation and forest degradation [IPCC SRCCL, 2019].

Offline (uncoupled) vegetation models simulations indicate that the extensive tropical and subtropical forests of the Americas could gradually transit towards a savanna-like vegetation with the most pronounced shifts (of up to 600km northward) from relatively stable forests to savanna-forest transitions occurring in the eastern Amazonian region (Huntingford et al. 2013; Anadon et al. 2014; Nobre et al. 2016) depending largely on the yet uncertain strength of the CO_2 fertilization effect and future dry season length, with important feedbacks on the flux of moisture from the forest to the atmosphere (Delphine Clara Zemp et al. 2017). More limited simulations for Central American rainforests under RCP 4.5 and 8.5 also support a transition in some areas to lower biomass tropical dry forest and savanna-like vegetation (Lyra et al. 2017). Such transitions from one biome type to another will cause major changes in forest structure, species compositions and overall biodiversity. Additionally, the difficulty of species to migrate through highly fragmented tropical forested regions (such as West Africa or South and Southeast Asia) and “non-analogue climates”, under a climate change scenario, poses extra pressure on tropical biodiversity to adapt and survive (Pörtner et al. 2021). Even in expansive tracts of forests such as in the Amazon, climate change is expected to become more important than deforestation by 2050 in causing the loss of tree species (Gomes et al. 2019). Tropical mountain biodiversity hotspots (e.g., Andes, Himalayas) are particularly vulnerable to species loss due to elevation range shifts (Sekercioglu et al. 2008). Under a 2°C increase scenario, a substantial reduction of tropical montane cloud forest in Kenya is estimated (Los et al. 2019).

CCP7.3.6 Climate Responses to Tropical Deforestation and Links to Forest Resilience

Since AR5 there has been meaningful advancement in understanding the climate effects of deforestation and concomitant changes in forest ecosystem resilience. The IPCC Special Report on Climate Change and Land (Jia et al. 2019) and IPCC AR6 WG1 (Douville et al. 2021) both describe significant climate-related changes resulting from tropical deforestation (*high confidence*).

Deforestation generally reduces rainfall and enhances temperatures and landscape dryness; effects that increase with the scale of forest loss, whereas reforestation and afforestation generally reverses these effects (*high confidence*) (Lawrence and Vandecar 2015; Alkama and Cescatti 2016; Khanna et al. 2017; Jia et al. 2019; Staal et al. 2020; Douville et al. 2021; Hofmann et al. 2021; Leite-Filho et al. 2021). There is also *medium evidence* from observations and modeling that deforestation enhances surface runoff (Douville et al. 2021). Whereas quantitative information is much more limited for other tropical regions, past deforestation in the Amazon has led to a small reduction in rainfall of -2.3 to -1.3%, shortening and delay of the wet season, and an estimated 4% increase in dryness (Leite-Filho et al. 2020; Staal et al. 2020; Douville et al. 2021).

Modeling studies estimate that large-scale tropical deforestation will contribute to average warming of the deforested areas with +0.61 ± 0.48°C and will lead to large changes in diurnal temperature ranges due to a reduction of nocturnal cooling (*medium confidence*) (Jia et al. 2019). Large-scale deforestation will also strongly decrease average regional precipitation and evapotranspiration and further delay the onset of the wet season, enhancing the chance of dry spells and intensifying dry seasons, but the magnitude of the decline depends on the scale and type of land-cover change (*high confidence*) (Delphine Clara Zemp et al. 2017; Jia et al. 2019; Douville et al. 2021; Gatti et al. 2021).

Continued forest landscape drying and fragmentation in connection with deforestation may also enhance surface flow variability (Farinosi et al. 2019; Souza et al. 2019) and will aggravate the risk of forest dieback (D. C. Zemp et al. 2017), elevate forest flammability (Alencar et al. 2015) and increase fire incidence (*high* *confidence*) (Aragão et al. 2018; Jia et al. 2019; Silveira et al. 2020; dos Reis et al. 2021), ultimately leading to savannization of many tropical rainforests (Sales et al. 2020). However, compositional heterogeneity and diversity of forest assemblages increases resilience against climate-enhanced forest degradation (Réjou-Méchain et al. 2021).

For the Amazon, deforestation (ca. 40% of the region) in combination with climate change will raise the prospect of passing a tipping point leading to large-scale savannization of the rainforest biome, but but uncertain remains that this will take place in the 21st century (Nobre et al. 2016; Jia et al. 2019; Douville et al. 2021). However, considering that the Amazon has already lost ca. 20% of its forests (Nobre et al. 2016), crossing the tipping point may not only create savannas of the deforested parts but may also result in precipitation reductions of 40% in non-deforested parts of the western Amazon due to a breakdown of the South American monsoonal circulation and the subsequent western cascade of precipitation and evapotranspiration (Boers et al. 2017). Other effects of forest degradation include loss of ecosystem services, biodiversity, carbon storage, and indigenous culture (Watson et al. 2018; Strassburg et al. 2019; Gatti et al. 2021), as well as potentially reduced hydropower capacity and agricultural production (Sumila et al. 2017) and increases in tropical diseases (Husnina et al. 2019).

The dearth of data for tropical forest regions other than the Amazon makes assessments of deforestation-related changes in temperature, precipitation and streamflow difficult (*high confidence*) and hampers estimates of tropical forest ecosystem health, biodiversity loss and vulnerability to current and future climatic and other pressures (*high confidence*). There is, hence, a strong need for increased investment in relevant data and research to narrow the knowledge gaps (Davison et al. 2021). Nonetheless, conclusions based on a newly developed tropical vulnerability index synthesizing remotely sensed land use and climate information indicate that forests in the Americas are already reaching critical levels to multiple stressors, while forests in Asia reveal vulnerability primarily to land-use change and African forests still show relative resilience to climate change (Saatchi et al. 2021).

CCP7.4 Social-Economical Vulnerabilities of Indigenous Peoples and Local Communities Living in Tropical Forests

Around 800 million people live in or in the immediate vicinity of tropical forests (Keenan 2015). Short-term impacts of climate change on biodiversity will exacerbate the inequalities affecting those livelihoods which heavily rely on forests (Pörtner et al. 2021).

Livelihoods, gender, land use change and dependency on forest resources for food, fuel, housing and other needs have been identified as key elements of vulnerability in Indigenous Peoples and rural communities in Africa and South America (high confidence) (Nkem et al. 2013; Field et al. 2014; Newton et al. 2016; Pearse 2017; IPBES 2018; Pörtner et al. 2021). Socio- economic vulnerability varies depending on the level of dependency of forest food consumption (Rowland et al. 2017), livelihood strategies and settlement patterns. In Cameroon (Nkem et al. 2013), nomadic hunter-gatherers and sedentary communities showed differences in their vulnerability, driven by their preferences in forest settlement locations for farming, hunting, fishing, gathering, trapping, and maintaining livestock.

Increasing temperatures, extreme climatic events, drought and fire will affect the proportion and frequency of forest resources availability. In communities of tropical America, Asia and Africa, social vulnerability factors identified include: deforestation pressures for agriculture expansion to cope with climate-induced food shortages, conflicts over access to forest land as a result of uncontrolled fire induced by higher drought frequency and severity, the availability of wild game, the work capacity, and the time consumed in work and gender-based differences (Blaser and Organization 2011; Bele et al. 2013; IPCC 2014). Although the size and quality of harvest in crops and Non-Timber Forest Products (NTFPs) will be affected, the literature reports the use of NTFPs, hunting, and fishing is less sensitive to climate change, and relevant for household incomes (Bele et al. 2013; Djoudi et al. 2013; Newton et al. 2016; Onyekuru and Marchant 2016). Data from tropical forests document the contribution of NTFPs to local livelihoods (Issaka 2018), with well-established NTFPs such as Brazil nut (Bertholletia excelsa), Rattan (Calamus and Daemonorops species), Rubber (Hevea species), Açai (Euterpe oleracea) showing promise for sustainable harvesting strategies which could reduce socio-economic vulnerability (Blaser et al. 2021).

The decrease of tropical forest area due to land use change will put additional pressures, threatening livelihood practices, traditional land arrangements, and customary rights of forest-dependent communities and impacting the Sustainable Development Goals (SDG) of Climate action and Life on Land (Djoudi and Brockhaus 2011; Tiani et al. 2015; Hurlbert et al. 2019). Globalized trade relations, agricultural expansion, illegal activities and violent conflicts have been identified as important non-climatic drivers of forest degradation (*high confidence*) (Barr and Sayer 2012; Rist et al. 2012; Shanley et al. 2012; Ruiz-Mallén et al. 2017; IPBES 2018; IPBES et al. 2018). Globally, about 70% of tropical forest areas occur outside protected areas. In Latin America and the Caribbean, Indigenous Peoples and local communities have predominant ownership of tropical forest lands, while in West and Central Africa and Asia, forested areas are largely State-owned with exacerbating problems of governance, inequity and conflict with customary land tenure systems (Blaser and Organization 2011).

Further research by experts and local stakeholders and Indigenous Peoples is required to design more accurate and comprehensive indicators (Huong et al. 2019). Solid evidence shows important knowledge and experiences that Indigenous Peoples and local communities contribute to disaster risk reduction and management (IPBES 2018a). Recognizing the land rights of Indigenous Peoples is among the most cost-effective actions to address climate and biodiversity risks, according to FAO and FILAC (2021). In Indigenous Peoples' forest lands in the Amazon basin, deforestation rates are up to 50% lower than in other forested areas (Ding et al. 2016), and indigenous management is correlated with reduced carbon emissions (Blackman and Veit 2018). Indigenous authors and local authors have pointed out the role of traditional systems of governance, knowledge and belief systems in the resilience of Indigenous Peoples and rural communities in the Amazonian and Andean region, by regulating seed access and the conservation of agrobiodiversity and tropical forest (Camico et al. 2021; Panduro Meléndez et al. 2021). In Philippines, the traditional land use system Muyong, promote sustainable agroforestry management based on customary land laws (Camacho et al. 2016). Participation of local stakeholders and the inclusion of a gender perspective contribute to prioritizing resource allocation and the development of effective legal frameworks for adaptation (Shah et al. 2013; Tiani et al. 2015; Ihalainen et al. 2017; Collantes et al. 2018). There is a need to combine quantitative and qualitative methods, and increase research efforts to integrated approaches; including multiscalar and interdisciplinary assessments of vulnerability (Djoudi et al. 2013; Guidi et al. 2018; FAO and CIFOR 2019).

[START BOX CCP7.1 HERE]

Box CCP7.1: Indigenous Knowledge and Local Knowledge and Community-Based Adaptation

Purely scientific knowledge, albeit indispensable, is insufficient to address climate change. Indigenous Knowledge systems, embedded in social and cultural structures, are integral to climate resilience and adaptation (*high confidence*) (Ajani 2013; Tengö et al. 2014; Hiwasaki et al. 2015; Roue and Nakashima 2018)[AR5 WG2 12.3.3, 14.3.1, 20.4.2 , SRCCL 4.8.1, 4.8.2, SR15 4.3.5]. Indigenous knowledge and local knowledge (IK and LK) and community-based adaptation (CbA) have received increasing recognition across all sectors (*high confidence*) (Reid and Huq 2014; Wright et al. 2014; MOSTE 2015)[SRCCL 4.1.6, 5.3.5, SR15 Box 4.3] (Figure Box CCP7.1.1). Forest Indigenous knowledge is closely linked to traditional land-use practices and local governance (Roberts et al. 2009); it is embodied in art, rituals, food, agriculture and customary laws, among others (Hiwasaki et al. 2015; Camico et al. 2021). CbA is a community led process based on its desires, priorities, knowledge and capacities; which empowers people as central players in climate change adaptation (Reid et al. 2009) [SRCCL 5.3.5].

CbA is related with concepts such as community and adaptive collaborative forest management. These approaches acknowledge the importance of cultural and socio-economic ties between communities and forests, along with community's authority and responsibility for forest sustainable management (Ajani 2013; Ellis et al. 2015; Torres et al. 2015).

Role of IK and LK and CbA for Climate Change Adaptation in Tropical Forests

Local forest and Indigenous forest management systems have developed over long time periods; generating social practices and institutions that have supported livelihoods and cultures for generations (*high confidence*) (Seppälä 2009; Martin et al. 2010; Parrotta and Agnoletti 2012; Camico et al. 2021).

Archaeological evidence shows that humans have manipulated tropical forests for at least 45 thousand years (*high confidence)*. Indigenous Peoples usually consider themselves as parts of socio-ecosystems, protecting the forest by maintaining healthy socio-ecological relationships and successfully adapting to environmental change (Speranza et al. 2010; Swiderska et al. 2011; Parrotta and Agnoletti 2012; Uprety et al. 2012; Mistry et al. 2016; Roberts et al. 2017) [AR5 WG2 12.3.2].

CbA ensures community engagement in bottom-up management and adaptation approaches (Simane and Zaitchik 2014; Keenan 2015). IK and LK and CbA can enhance adaptation in many ways, including through knowledge generation, ecosystem monitoring, climate forecasting, increased resilience and response to climate extremes and slow onset events (Speranza et al. 2010) [AR5 WG2 12.3.3; SRCCL 4.8.2] (Figure Box CCP7.1.1).

Integration of IK and LK Systems, CbA and Modern Scientific Systems

Several authors have highlighted the need to foster a respectful a dialogue between IK and LK and modern science towards a holistic research model (*high confidence*) (Berkes 2010; Ajani 2013; Tengö et al. 2014; Roue and Nakashima 2018)[AR5 WG2 12.3.3, 14.2.2]; but few ecological studies have attempted this integration (Keenan 2015; Vadigi 2016). Examples in tropical forest ecosystems include topics such as monitoring climate impacts; local climates; seed, water and land management resilience-increasing practices and climate threats to traditional agriculture (Parrotta and Agnoletti 2012; Fernández-Llamazares et al. 2017; Camico et al. 2021; Panduro Meléndez et al. 2021). A growing number of methods are available to help this dialogue [SRCCL 7.5.1] (Reid et al. 2009; Tengö et al. 2014; Tengö et al. 2017; Roue and Nakashima 2018)(Figure Box CCP7.1.1). While there is expanding interest among decision-makers, researchers, Indigenous Peoples and civil society on IK and LK (Hiwasaki et al. 2015; Maillet and Ford 2016), gaps remain regarding links between place-and-culture dimensions and adaptive capacities (Ford et al. 2016).

Enhancing Adaptive Capacity Through IK and K and CbA: Lessons Learned

Useful lessons can be drawn from experience to effectively incorporate IK and LK and CbA in adaptation strategies. A number of barriers to adaptation have also been recognized (Figure Box CCP7.1.1). Considering that IK and LK is increasingly threatened by colonization, acculturation, dispossession of land rights, and environmental and social change, among others [AR5 WG2 12.3.3; SR5 4.3.5] (Seppälä 2009) highlighted the importance of supporting community efforts to document, vitalize and protect it. It is essential to consider goals, identity and livelihood priorities of Indigenous Peoples and local communities, including those beyond natural resource management (Reid et al. 2009; Diamond and Ansharyani 2018; Zavaleta et al. 2018). Adaptation processes are more *likely* to be transformational when they are locally driven (*medium confidence*: *medium evidence, high agreement*) (Chung Tiam Fook 2015; Chanza and De Wit 2016). This requires adaptive institutional frameworks, capable of navigating the complex dynamic of socio-ecosystems (*medium confidence*: *medium evidence, high agreement*) (Locatelli et al. 2008; Simane and Zaitchik 2014)[AR5 WG2 12.3.2; SR15 5.3.1]. It is important to consider power relations and priority differences to avoid causing social disruption and inequality. “We need to keep asking: Who benefits? Who loses? Who is empowered? Who is disempowered?” (Reid et al. 2009).

Finally, vulnerability and adaptive capacity have a historical and geopolitical context, conditioned by value systems and development models. Forest management strategies must take into account the wider picture if they seek to be not just temporally effective (at best), but transformative and sustainable over time (*high confidence)* (Chung Tiam Fook 2015; Chanza and De Wit 2016).

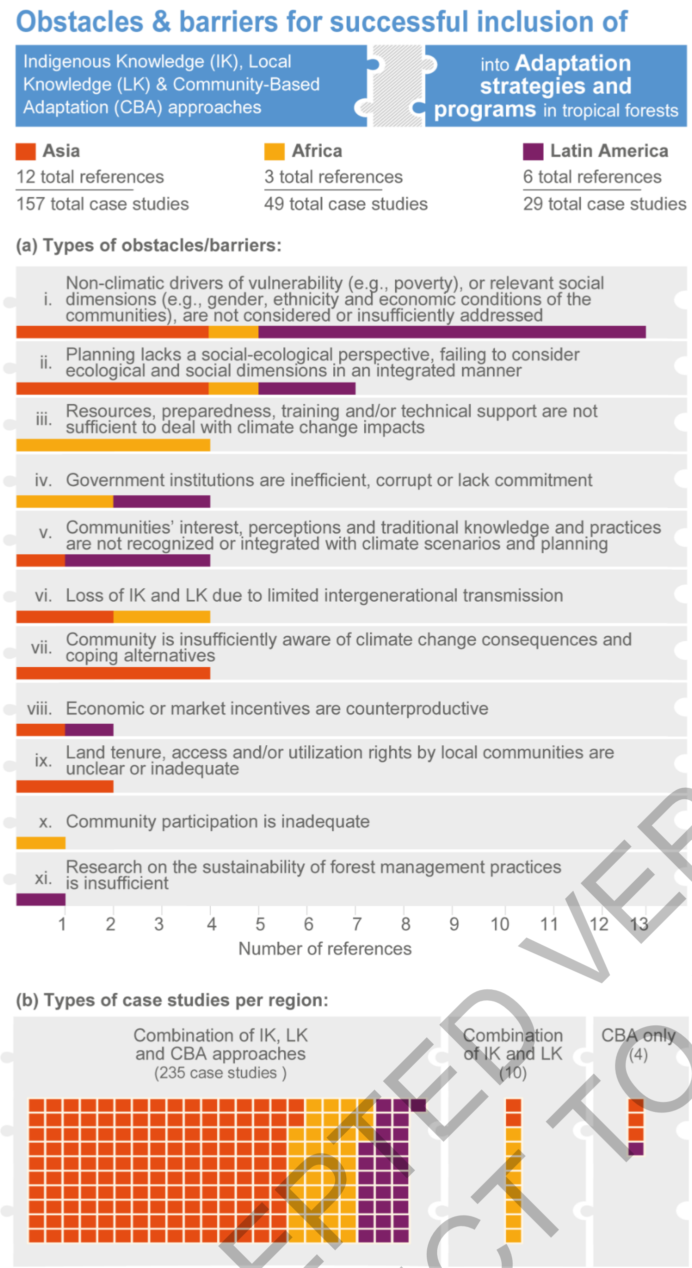

Figure Box CCP7.1.1: Main obstacles and barriers reported for successful IK and LK and CBA approaches in adaptation strategies and programs for tropical forests.
Panel (a): Obstacles and barriers ranked by the number of references in which they were identified. (One reference can identify more than one barrier, so numbers of references by barrier are not additive). Panel (b): Distribution of cases studies according to approach (IK and LK, CBA or a combination of both). One reference can include one or more case studies. See countries included by continent and references in the Supplementary Material (SMCCP7.2)

[END BOX CCP7.1 HERE]

CCP7.5 Adaptation Options, Costs, and Benefits

Ecological adaptation and other spontaneous responses to climate change are discussed in (Settele et al. 2015) and [AR6WGII_Ch2]). Here we consider the role of humans in managing the adaptation of tropical forests to climate change. The focus is on human-assisted adaptation options that help to maintain tropical forest ecosystems and not on the use of forests to supply provisioning services, such as timber, which is covered in [AR6 WGII_Ch5]. Forest management and agroforestry are discussed, but only with regard to their role in contributing to the adaptation of tropical ecosystems now and in the future. Maintaining ecosystems has a range of co-benefits for humans including through 'ecosystem-based adaptation' these are explored in [Chapter 1 Box 1.3; Cross-Chapter Box NATURAL in Chapter 2, Box CCP7.2]. Although there are a number of potentially valuable response options, it is clear that certain hazards, such as heat waves, may be impossible to manage at the forest community level and require long-term interventions at the landscape scale. Similarly, it will be difficult for forest managers to adapt to indirect climate-related ecosystem disturbances such as loss of pollination agents, invasive species, or pest and diseases outbreaks (Allen et al. 2010; Anderegg et al. 2020). Equally important in adapting to increased pressure from climate change are efforts to minimize disturbance from non-climatic stress factors (e.g. overharvesting, pollution, and land use change (Malhi et al. 2014; Keenan 2015; Barlow et al. 2016; Pörtner et al. 2021). Under some emissions scenarios, projected climate change impacts are of such severity that no adaptation measure is *likely* to protect natural forest systems, e.g. with warming of 4 ˚C, some tropical forests are at risk of die-back from high temperature (Malhi et al. 2014; Settele et al. 2015; Trumbore et al. 2015).

Actions to protect the extent or reduce the disturbance pressure on forest systems contribute to the capacity of these systems to respond to climate change (increasing resistance and resilience) (*high confidence*) (Millar et al. 2007; Schmitz et al. 2015; Settele et al. 2015; Sakschewski et al. 2016; Hisano et al. 2018). Furthermore, if implemented sufficiently well, efforts to manage and restore forests also improve the capacity of forest systems to respond to future climate stressors (increasing resilience and responsiveness). Table CCP7.3 gives an overview of adaptation strategies for tropical forests within the framework of protect, manage, restore (Sayer et al. 2003; Pörtner et al. 2021). In assessing the available adaptation options, it can be useful to distinguish between actions focused on protecting forest extent, managing biodiversity, managing ecosystem function, or restoring ecosystem services (Seppälä 2009), Figure CCP7.5 and Table CCP7.4 give a detailed assessment of the major adaptation options in this context. Beyond these specific interventions, and in several cases underpinning them, there is an increasing awareness that effective management and adaptation of tropical forests requires an appreciation of IKLK and community-based adaptation in order for implementation to be meaningful, these approaches are assessed in [Box CCP7.1]

CCP7.5.1 Adaptation Options at Different Scales

To retain functioning tropical forests, adaptation will need to take place across many scales from individual stands, to interconnected landscapes, and upwards to regional and global policy changes. From a global perspective the most effective adaptation and mitigation option is to reduce and reverse the loss of area in tropical forest ecosystems (Alkama and Cescatti 2016; B. W. Griscom et al. 2017). Maximizing tropical forest extent has well described benefits in mitigating CO2 emissions and in the role of forests regulating global climate (*high confidence*) (Smith et al. 2014). For nations with tropical forests, adaptation is largely achieved through sustainable management of forested areas, enforcing the land rights/land tenure of Indigenous Peoples, and through establishment of Protected Areas (Table CCP7.4; (Seppälä 2009; Pörtner et al. 2021)). Some of this is achieved through schemes incentivizing landowners to retain tree cover for the express purpose of mitigating climate change impacts (e.g. PES, REDD+). For nations outside of the tropics, there is a need to regulate the global drivers of forest loss, such as the consumption of agricultural commodities and of non-sustainable forest products (including timber) (CCP7.3; (CCP 7.3; Henders et al. 2015 Nolte et al., 2017, Pendrill et al., 2019).

At a landscape scale, increasing forest cover and maintaining biodiversity-friendly land-use outside forests increases ecosystem resilience to climate change (and other disturbances) and allows for climate-driven species migration e.g. Table CCP7.3- protect; (Schmitz et al. 2015; Aguirre and Sukumar 2016)). Ensuring forested areas are large and/or interconnected including the use of specific climate refugia and climate corridors is recommended for climate adaptation (*high confidence*) (Schmitz et al. 2015; Settele et al. 2015; Simmons et al. 2018; Pörtner et al. 2021). For habitats or species pushed to the edge of their range, area-based conservation needs to take account of the future climate space and facilitate movement of species through connectivity or assisted migration (Seppälä 2009; Schmitz et al. 2015; Pörtner et al. 2021). Maintaining functioning forest ecosystems is vital due to biophysical, biological (biodiversity-driven) and socioeconomic interactions that contribute to ecosystem resilience (Pielke Sr et al. 2011; Malhi et al. 2014; Lawrence and Vandecar 2015; Alkama and Cescatti 2016; Sakschewski et al. 2016). Protecting forested areas can be achieved through vertical integration of policies at national, subnational and local levels and effective stakeholder empowerment (Meijer 2015). Community-based and ecosystem-based adaptation approaches provide an overall strategy to help achieve these goals [Cross-Chapter Box NATURAL in Chapter 2] (Locatelli et al. 2010; Cerullo and Edwards 2019). In addition to conservation of tropical forests, restoration and afforestation can be effective climate adaptation measures (e.g. Table CCP7.3- restore)

(Arora and Montenegro 2011; Perugini et al. 2017). The technical requirements for such adaptation measures are similar to those required for forest landscape restoration (Mansourian and Vallauri 2005; Mansourian et al. 2017; Shimamoto et al. 2018; Philipson et al. 2020). Agricultural intensification has been proposed as one method to reduce pressure on remaining forested land, although the overall carbon impact of such approaches must be considered (Cross-Chapter Box 6 in SRCCL, Shukla et al. 2019; Cerri et al. 2018; Kubitza et al. 2018).

At the forest community level, adaptation options aim to protect the forest microenvironment and retain biodiversity through forest management (e.g. Table CCP7.3- manage; (Keenan 2015; Jactel et al. 2017)). In Protected Areas this would typically involve reinforcing existing conservation objectives through adaptive management (Salafsky et al. 2001; Ellis et al. 2015; Tanner-McAllister et al. 2017; Hagerman and Pelai 2018), including support for natural regeneration (Chazdon et al. 2016). It is also possible to improve forest cover and interconnectivity through restoration or afforestation. There are many technical guides to improve the implementation and success rate of such approaches (Table CCP7.4) (Lamb and Gilmour 2003; Shimamoto et al. 2018; Strassburg et al. 2019)) and funding support specifically aimed at climate change adaptation and mitigation (e.g. REDD+). In some instances, climate change can alter climate suitability to the extent that managers need to allow for a transition to a new habitat type (e.g. from tropical forest to savanna), adaptive management can help recognize and facilitated these transitions (Seppälä 2009; Schmitz et al. 2015; Lapola et al. 2018). Depending on local conditions it will be necessary to adapt to specific stress factors that are *likely* to increase in prevalence or severity due to climate change, e.g. heat waves, drought events and forest fires (Allen et al. 2010; Malhi et al. 2014; Seidl et al. 2017). Although it is typically not possible to link individual events or adaptation measures to climate change; the effectiveness of technical interventions has been illustrated in a broader forest management context. Table CCP7.4 assesses the costs and benefits of different adaptation options based on the available literature. However, it should be noted that there is lack of information on many potential adaptation interventions, especially in the context of tropical forests (Locatelli et al. 2010; Bele et al. 2015; Keenan 2015; Hagerman and Pelai 2018). The sections below and Figure CCP7.5 offer a framework for optimizing management of complex tropical forest ecosystems within a landscape context, through a range of interconnected adaptation options.

CCP7.5.2 Adaptation Response Options

Forests will be affected by several climate change impacts that will require forest management towards fulfilling four objectives: maintain forest area; facilitate biodiversity adaptation; maintain healthy functioning forest ecosystems; and restore ecosystem services (including productive capacity) (Seppälä 2009), which complement the more conventional approaches to protect, manage and restore forests (Sayer et al. 2003). This is dependent on location-specific conditions that are defined by the type of forest and land tenure regimes or dominant actors across forest landscapes. The analysis here proposes 10 adaptation responses that focus on the adaptation potential of tropical forests to climate change and are linked to the management objectives identified (Figure CCP7.5). Each response option (1–10) implies variable economic costs and benefits, influenced by location-specific conditions, including several important non-monetized benefits. The figure suggests the most relevant situations in which the different response options hold greater potential to meet the forest management objectives for addressing expected climate change impacts.

This assessment considers the economic costs and benefits of 10 response options in their contribution to adaptation of tropical forests to climate change impacts but also includes non-market costs that are more difficult to quantify (e.g. cultural values), which are borne by different stakeholders (Chan et al. 2016; Pascual et al. 2017). Similarly, benefits also include the social and environmental benefits that result from adaptation options over extended time horizons. Economic costs and benefit-cost ratios suggest the short-term economic potential of different options, but responsibly designed adaptation measures involving a combination of different response options and embracing a long-time horizon have the potential to provide significant social and climate benefits over the coming 50 years or more.

Table CCP7.3: Overview of adaptation strategies for tropical forests. This table includes key policy frameworks and common management approaches with potential for adapting native forests to increased disturbance from climate hazards. Details on each management approach and the associated literature are given in Table CCP7.4: Costs and Benefits of Adaptation Options in Tropical Forests.

	Strategy	Expected contribution to climate adaptation
Protect	Protected Areas	Maintaining forest extent builds resistance and resilience to climate change (Seppälä et al., 2009; Schmitz et al., 2015).
	Area-based conservation / Climate refugia	Where forests are under threat from progressive warming, protection of less disturbance prone areas (e.g. higher altitude stands) allows for migration and recolonization improving the ability of the whole ecosystem to respond to climate change (Schmitz et al., 2015; Pörtner et al., 2021).
	Buffer zones	Maintaining buffer zones around protected forests builds resistance and resilience to climate change and allows for adjustment of boundaries, under future conditions (Seppälä et al., 2009; Schmitz et al., 2015).
	Avoid deforestation	Reducing loss of trees due to non-climate stressors, protects forest extent and builds resistance and resilience to climate change (Locatelli et al., 2010; Smith et al., 2019).
	Public education / awareness	Publicizing the role of forests in supporting human society can reduce anthropogenic pressures on forested areas (Seppälä et al., 2009; Hagerman & Pelai, 2018).
Manage	Vulnerability assessment and monitoring programs	Recognising changes in climate and in disturbance regimes allows for other management interventions, such as area-based conservation and assisted migration, to be implemented (Schmitz et al., 2015; Hagerman & Pelai, 2018).
	Adaptive management / climate services	Adaptive management along with information on the changing climate can improve the capacity of forest managers to respond to climate change (Seppälä et al., 2009; Tanner-McAllister et al., 2017).
	Strengthen land tenure	Strong land tenure, e.g. for Indigenous Peoples, often leads to more sustainable management of forested areas, so building resistance and resilience of climate change (Porter-Bolland et al., 2012; Garnett et al., 2018).
	Conserve biodiversity, promote mixed stands	Within managed forests, using diverse planting stock and managing for biodiversity improves resilience to disturbances from future climate changes (Keenan, 2015; Pörtner et al., 2021).
	Fire prevention and management	The use of fire suppression, fire breaks, controlled burning and water table maintenance can build resistance to climate change driven wildfires, in both managed and natural systems (Stephens et al., 2013; Musri et al., 2020; Bowman et al., 2020).
	Sustainable forest management	Within managed forests, vegetation control to manage tree density and stand conditions can build resistance to climate driven disturbance such as fire (Seppälä et al., 2009; Pörtner et al., 2021).
Restore	Increase connectivity	Providing connection corridors between forested areas builds resilience and helps the system response to climate change. This can include thermal corridors that allow for species migration under progressive climate change (Schmitz et al., 2015; Hagerman & Pelai, 2018).
	Forest restoration / assisted natural regeneration	Forest restoration helps restore forest extent and connectivity, and can reduce edge pressure, improving resilience and the capacity to respond to future climate stressors. In some cases, assisted migration and the use of planting stock selected for tolerance to climate change may be appropriate (Locatelli et al., 2015a; Pörtner et al., 2021).
	Agroforestry / trees on farm	In degraded areas, such as buffer zones and mosaic landscapes, planted trees can reduce resource pressure on intact forest, improve soil conservation, regulate temperature and water cycles, and increase resilience through ecological processes (Jose, 2009; Lasco et al., 2014).
	Indigenous and Local knowledge of ecosystems	Incorporating Indigenous and Local knowledge can improve the ability to protect and sustainably manage forest systems so building resilience (Seppälä et al., 2009; Porter-Bolland et al., 2012).

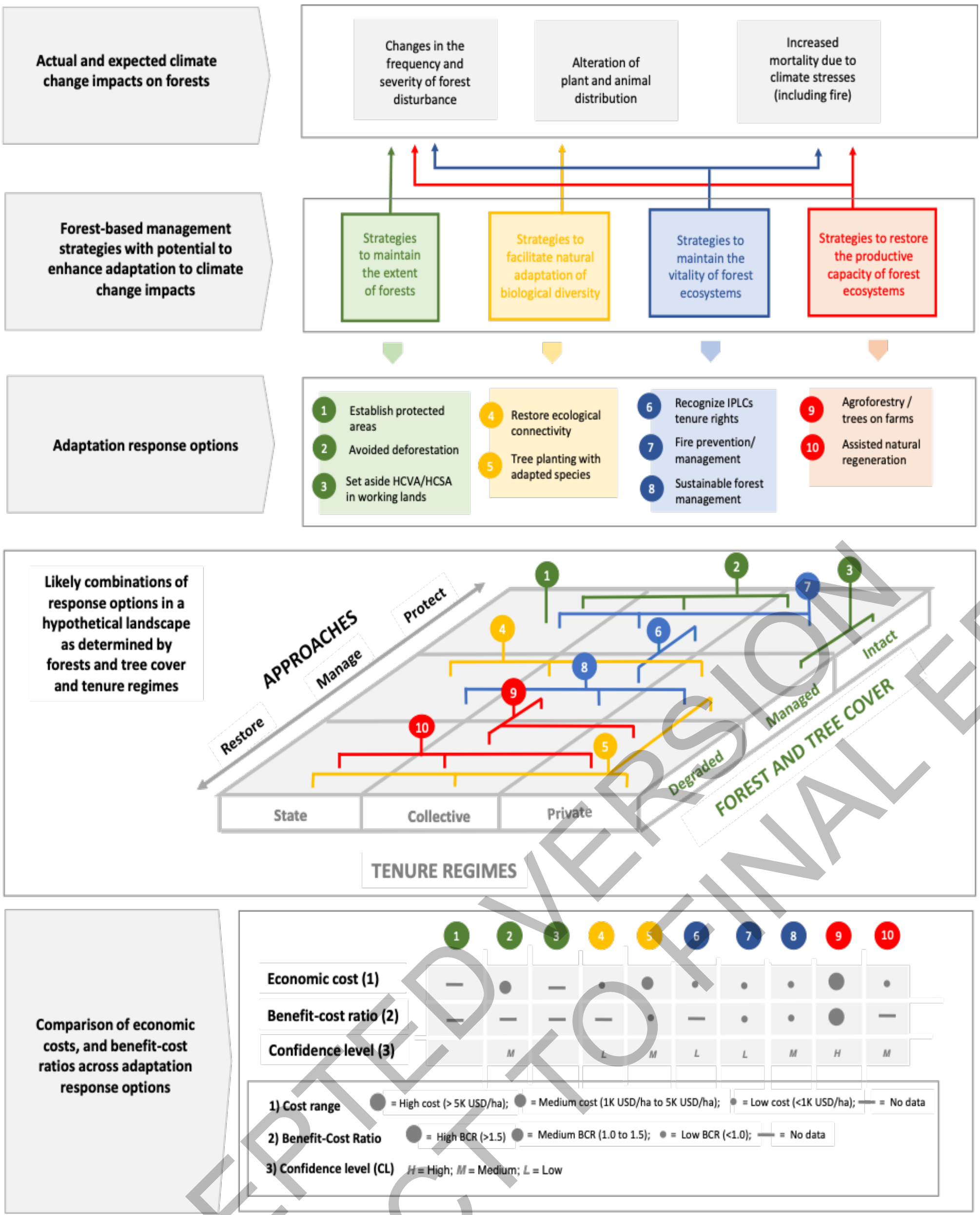

Figure CCP7.5: Framework to assess adaptation response options in tropical forests by adopting a landscape perspective as determined by types of forests and tree cover across different tenure regimes. Notes: HCVA = High Conservation Value Areas; HCSA = High Carbon Stock Areas; IPLC = Indigenous Peoples and Local Communities. The information supporting this figure originates from an extensive literature review that is included in this section, Table CCP7.4. The assessment of confidence levels is based on the judgement of the authors based on the reviewed literature and follows IPBES guidelines.

CCP7.5.3 Costs

The cost of implementing adaptation options varies widely and will change based on the location, time horizon, and who bears the cost. As a result, most existing estimates are offered in broad ranges that include only partial cost estimates. Here we group the adaptation costs into three categories, low (<USD1000/ha), medium (between USD1000/ha and USD5000/ha) and high cost options (>USD5000/ha).

- Low cost options are those estimated to cost less than USD 1000 per ha and include recognition of tenure rights of Indigenous Peoples and local communities (Hatcher 2009), restoring ecological connectivity (Crossman and Bryan 2009; Torrubia et al. 2014), fire prevention and management (Bronson W Griscom et al. 2017; Arneth et al. 2019), assisted natural regeneration (Cury and Carvalho

2011; Lira et al. 2012; MMA 2017; Silva and Nunes 2017), and sustainable forest management (Boltz et al. 2001; Holmes et al. 2002; Pokorny and Steinbrenner 2005; Medjibe and Putz 2012; Singer 2016).
- Medium cost options are those estimated to cost between USD 1000 and USD 5000 per ha and include estimates for tree planting (Rodrigues 2009; Campos-Filho et al. 2013; Silva and Nunes 2017; Nello et al. 2019) and avoided deforestation (Kindermann et al. 2008; Overmars et al. 2014; Smith et al. 2019).
- High cost options are those estimated to cost more than USD 5000 per ha and include actions associated with agroforestry systems, particularly the most biodiverse systems (Raes et al. 2017; Nello et al. 2019).
- Costs per hectare are either not available or vary too widely for several options, including protected areas (Balmford and Whitten 2003; Bruner et al. 2004), and high value conservation areas in working lands (Naidoo and Adamowicz 2006). Bronson W Griscom et al. (2017) provided recent estimated costs for many of the above adaptation options; in most cases these costs are much lower than other estimates referenced here, which are particularly focused on tropical forest landscapes.

While economic costs constitute an important factor in determining the feasibility of options, there are other factors that have an important influence on the viability of the options including opportunity costs, transaction costs, and social feasibility, which are not included in this analysis. For example, options such as recognition of rights for Indigenous Peoples and local communities can be a low-cost option but often face political opposition (RRI 2021) including from some conservation organizations; fire prevention and management require political coordination across multiple governance levels (Fonseca-Morello et al. 2017); and sustainable forest management can be seen as a less attractive option when compared to other more profitable land uses (Köthke 2014). Table CCP7.4 offers a more detailed assessment of the costs included, along with a reference to the costs for society.

CCP7.5.4 Benefits

Estimates of economic benefits across options tend to vary greatly, largely based on the scale of operations, and the market and institutional contexts in which they are implemented. The longer-term non-monetary benefits tend to be larger than has been acknowledged in the past (Chan et al. 2016; Pascual et al. 2017; UNEP 2021). The shorter-term horizon of the economic benefits of adaptation options suggest that benefit-cost ratios of investments are higher in more biodiverse agroforestry systems in comparison with simpler ones (Miccolis et al. 2016), and agroforestry system benefits are comparatively higher compared with commercial tree planting depending on the species (Table CCP7.4 (Nello et al. 2019)).

All the objectives here support not only a large number of local people in fulfilling their livelihoods, but often provide services to distant urban populations as well. The benefits differ according to which of the four forest landscape management objectives is prioritized (Table CCP7.4):

- objectives that seek to maintain the extent of forests contribute to improved landscape continuity, persistence of species and metapopulations (including floral recruitment) (Nordén et al. 2014), maintaining hydrological cycles (Creed et al. 2011), and avoiding surface temperature increases (Perugini et al. 2017). In many cases High Conservation Value Areas (HCVAs) are based on the presence of threatened or endemic species or dense, carbon-rich forest ecosystems (e.g. primary forest) (Jennings et al. 2003).
- objectives that prioritize natural regeneration and adaptation of biological diversity allow greater opportunity for climate refugia (Morelli et al. 2017; Simmons et al. 2018), provide increased dispersal opportunities for different species (Christie and Knowles 2015), increase flora and fauna diversity, and may provide small benefits in reducing warming (Arora and Montenegro 2011).
- objectives to maintain and enhance the quality and persistence of vital forest ecosystems contribute to securing the provision of habitat, maintain soil structure and fertility, and regulate water quantity and quality (Imai et al. 2009; Putz et al. 2012).
- objectives that prioritize the restoration of ecological productivity of degraded forest ecosystems and landscapes contribute to increased biodiversity conservation, soil structure and fertility, nutrient cycling, water infiltration/water recharge, erosion control and climate regulation (Seppälä 2009; Shimamoto et al. 2018; Pörtner et al. 2021).

CCP7.5.5 Strategic Approaches to Combine Response Options

While adaptation costs and benefits of response options differ, their benefit-to-cost ratios are almost always positive, particularly in the longer term (Müller and Sukhdev 2018; Chausson et al. 2020; Seddon et al. 2020; Baste et al. 2021). However, implementation of adaptation actions can be economically unviable if the benefits accrue over longer periods of time because development banks apply much higher discount rates to low income countries than the standard rates (Watkiss 2015). Achieving conditions that do not disincentivize against, and rather encourage investments in nature-based solutions to protect, sustainably manage, or restore tropical forest landscapes is therefore critical to enhancing their implementation (UNEP 2021).

In addition, implementation of response options should consider equity aspects to ensure that the costs and benefits of actions within a landscape are equitably distributed among public institutions, private enterprise, and civil society (Verdone 2015). Strategic approaches to restoring ecosystems can increase conservation gains and reduce costs (Shimamoto et al. 2018; Strassburg et al. 2019). Cost-effective solutions that consider multiple costs and benefits need a "compromise solution" between short and long-term social and economic gains. Pursuing spatial allocations for adaptation options has the potential to deliver greater benefits at lower costs, therefore aligning aims for tropical forest adaptation, species conservation, and climate mitigation targets with the interests of farmers under short and long time horizons (Beatty et al. 2018).

Table CCP7.4: Costs and Benefits of Adaptation Options in Tropical Forests.

Climate change impact	Adaptation measures	Expected contribution to adaptation	Context/Location of implementation	Economic costs	Costs to society	Benefits for forest ecosystems	Benefits/Impacts to people
1. Forest management strategies to maintain the extent of forests							
Changes in the frequency and severity of forest disturbance	Avoid deforestation	Forests counteract wind-driven degradation of soils, and contribute to soil erosion protection and soil fertility enhancement for agricultural resilience (Locatelli *et al.* 2015a). The impact of reduced deforestation may be higher when the large biophysical impacts on the water cycle (and thus drought) are taken into account (e.g. (Alkama and Cescatti 2016)). Reducing deforestation and habitat alteration contribute to limiting infectious diseases (e.g. malaria) (Karjalainen *et al.* 2010). Avoiding deforestation contributes to climate change mitigation due to reduced carbon emissions (Smith *et al.* 2019).	In private lands (individual and collective) and in state lands, in areas with larger presence of intact forests or mosaic agriculture and forest lands under management.	500-2600 USD ha^{-1} (Kindermann *et al.* 2008; Overmars *et al.* 2014; Smith *et al.* 2019). (1) 20-200 USD ha^{-1} (Bronson W Griscom *et al.* 2017; Arneth *et al.* 2019) (global estimate).	Opportunity costs associated with different alternatively productive land uses (Kindermann *et al.* 2008).	Landscape continuity, persistence of species and metapopulations (including floral recruitment) (Nordén *et al.* 2014). Maintained hydrology (Creed *et al.* 2011), and flood mitigation. Avoided surface temperature increases (Perugini *et al.* 2017) Protects other regulatory functions of forests, with positive impacts on human health.	Potential to affect the lives of 1-25 million people globally (low confidence) (Keenan 2015; UNISDR and CRED 2015; Smith *et al.* 2019).
	Protect and/or increase the size and number of protected areas, especially in 'high-value' areas	Protected areas play a key role for improving adaptation (Lopoukhine *et al.* 2012; Watson *et al.* 2014), through reducing water flow, stabilizing rock movements, creating physical barriers to coastal erosion, improving resistance to fires, and buffering storm damages. Primary forests sustain tropical biodiversity (Gibson *et al.* 2011), thus protecting intact forests preserves current patterns of biodiversity (Schmitz *et al.* 2015). (2)	Mainly established in state lands where there is dominance of intact forests, in some cases overlapping with Indigenous territories.	Costs include recurrent management costs, system wide costs, and establishment costs. The cost per ha decreases with increased area (Balmford and Whitten 2003; Bruner *et al.* 2004).	Potential land use and tenure conflicts over protected area expansion. 'High value' areas are often priority areas for human activity (e.g. lowlands) (Venter *et al.* 2014). Management costs (Bruner *et al.* 2004).	May create additional dispersal corridors and support metapopulations for forest species increasing ecosystem resilience (Nordén *et al.* 2014). Improved hydrology (Creed *et al.* 2011) Protected areas contribute to income generation through tourism (Snyman and Bricker 2019).	Empirical studies of protected areas that use impact evaluation methods, provide evidence that parks help increase household incomes (Mullan *et al.* 2009), poverty alleviation and environmental sustainability (Andam *et al.* 2010).

	Set aside High Value Conservation Areas (HVCA) and High Carbon Stock Areas (HCSA) in working lands	Setting aside HCVA and HCSA within agriculture or tree-crop plantations has benefits for preserving endemic species, and some ecological services (e.g. pollination services from insects)) (Scriven *et al.* 2019) [(3)]	Established in private intact and managed forest lands often allocated to mid- and large-scale plantations.	Opportunity costs to landowners who would lose working land/productive area to HCVA or HCSA. Management costs (Naidoo and Adamowicz 2006).	□Opportunity costs to landowners who would lose working land/productive area to HCVA or HCSA. □Management costs (Naidoo and Adamowicz 2006).	□In many cases HCVA are based on the presence of threatened or endemic species or dense, carbon-rich forest ecosystems (e.g. primary forest) (Jennings *et al.* 2003).	HCVA also provide ecosystem services, and therefore can contain valuable economic benefits; forests provide for some basic needs of local communities (health and subsistence) as well as traditional/ cultural identity (Seppälä 2009; Karjalainen *et al.* 2010).
2. Forest management strategies to facilitate adaptation of biological diversity							
Alteration of plant and animal distribution	Restore ecological connectivity through the establishment of corridors	Conserve biodiversity by enabling natural migration of species to areas with more suitable climates (Malcolm *et al.* 2002), maintaining connectedness, especially between various protected areas, and ensuring that different stages of forest development are present (Seppälä 2009). Building corridors creates landscape permeability for plant and animal movement (Schmitz *et al.* 2015).	Corridors are implemented in managed lands across state, collective and private tenure regimes circumscribed to specific project targeted areas.	60-1294 USD ha^{-1} (in USD 2019) (Crossman and Bryan 2009; Torrubia *et al.* 2014)	□Land use opportunity costs, financial costs of land acquisition and restoration (Naidoo and Adamowicz 2006). Research and pilot costs of different corridor connection methods (Naidoo and Adamowicz 2006).	□Landscape connectivity allows greater opportunity for climate refugia (Morelli *et al.* 2017; Simmons *et al.* 2018) and the restoration of ecosystem patches of native forests can provide dispersal opportunities for different species using alternate successional stages (Christie and Knowles 2015). □Improved hydrology.	Ecosystem services could be enhanced (e.g., hydrological benefits, soil conservation, health, recreational and cultural benefits through establishment and restoration of green spaces).
	Mixed planting with native species tree planting, with consideration of intraspecific genetic diversity of seedlings	Reforestation is an important climate change adaptation response option (Reyer *et al.* 2009; Locatelli *et al.* 2015b; Ellison *et al.* 2017), and can potentially help a large proportion of the global population to adapt to climate change and related natural disasters. Native tree planting aimed at increasing resilience should include planting genotypes tolerant of drought,	Tree planting is implemented in degraded lands across different state, collective and private lands	Planting of seedlings 978-3450 USD ha^{-1} (in USD 2019) (Chabaribery *et al.* 2008; Rodrigues 2009; Campos-Filho *et al.* 2013; MMA 2017; Silva and	Loss of water yield (at least on an annual average basis) due to increased evapotranspiration Reforestation helps maintaining base flow during the dry season may reduce the	□Better water retention capacity; reduced risk of erosion, landslides □Carbon gain. □Increases both flora and fauna biodiversity. □In cases of reforestation/afforestation, small benefits in reducing warming are expected	Reforestation/afforestation has the potential to impact the lives of >25 million people globally (Medium confidence) (Reyer *et al.* 2009; UNISDR and CRED 2015; Sonntag *et al.* 2016; Bronson W Griscom *et al.* 2017; Smith *et al.* 2019) (global estimate). No availability

		insects and/or disease, as well as increasing the genetic diversity within species used for planting and recognizing provenance. Tree planting should avoid conversion of natural ecosystems including grasslands and savannahs (Bond and Zaloumis 2016).		Nunes 2017; Nello *et al.* 2019) 20-200 USD ha^{-1} (Arneth *et al.* 2019), for reforestation and forest restoration (Bronson W Griscom *et al.* 2017) (global estimate).	amount of water available for people downstream (Ellison *et al.* 2017). Research costs on genetic varieties and Implementation	(Arora and Montenegro 2011). □Increased potential for adaptive evolutionary responses within populations to the varied effects of climate change (drought, disease, etc.) (Puettmann 2014).	of information on differentiated impacts from reforestation and afforestation.
3. Forest management strategies to maintain the vitality of forest ecosystems							
Changes in the frequency and severity of forest disturbance	Recognizing the rights of Indigenous Peoples and local communities	Granting tenure rights to Indigenous people has potential to maintain forest, and ensure provision of ecosystem services, thus supporting local strategies for adaptation to climate change threats (Porter-Bolland *et al.* 2012)	Recognizing local tenure rights takes place in land belonging to Indigenous Peoples and local communities across all different forest and trees conditions	0.05-9.96 USD ha^{-1} (Hatcher 2009). Include the costs of mapping, delimitation, and titling. (RRI 2021) estimates the following costs: US$5 per ha for large projects, $22.5 per ha for medium, sub-national projects, and US$50 per ha for small investments.	□Costs to local populations for protecting forest lands, and opportunity costs for avoiding land conversion (Hajjar *et al.* 2016).	□Landscape continuity, persistence of species and metapopulations (including floral recruitment) (Nordén *et al.* 2014).	Some estimates indicate that Indigenous people manage or have tenure rights over at least ~38 million km^2 (Garnett *et al.* 2018) (global estimate). Recognition of rights often translates into positive social and environmental benefits (RRI 2021), yet they may differ depending on local conditions
Increased mortality due to climate stresses (including fire)	Within production forests, practice sustainable logging by embracing reduced-impact	Some production forests can retain most ecosystem functions and services, and a similar species richness of animals, insects, and plants to that found in nearby old-growth forest but can be more susceptible to defaunation and fire (Edwards *et al.* 2014). Sustainable	SFM is undertaken at a large scale in public forests allocated as concessions, and at smaller scales in private and	70 to 160 USD ha^{-1} (Singer 2016) 169-345 USD ha^{-1} (in USD 2019) (Boltz *et al.* 2001; Holmes *et al.* 2002; Pokorny	□The tendency of interventions is a (direct or indirect) reduction of diversity because the natural interest of the forest owner is to favor	□Secures the provision of species habitat □Soil structure and fertility □Regulates water quantity and quality □Carbon storage (Imai *et al.* 2009)	The benefits of Sustainable Forest Management have the potential to affect the lives of >25 million people globally (low confidence) (UNISDR and CRED

	logging (RIL) and other practices	Forest Management plays a role in adaptation by ensuring that through long-term forest management the diversity of forests is maintained as well as benefits from forest resource use (Putz *et al.* 2012). Improved forest management positively impacts adaptation by limiting the negative effects associated with pollution (of air and fresh water), diseases, and exposure to extreme weather events and natural disasters (e.g., (Smith *et al.* 2014)) [4]	community forests lands	and Steinbrenner 2005; Medjibe and Putz 2012) \$20-\$200 ha^{-1} (Bronson W Griscom *et al.* 2017; Arneth *et al.* 2019) (global estimate)	commercial species.		2015; Smith *et al.* 2019) (global estimate)
	Reduce the incidence of fire hazard and improve fire management	As fire hazard increases in some forests with climate change, adaptation measures to reduce fire hazard will be needed (Seppälä 2009).	Fire prevention and management is practiced in private lands (individual and collective) and state lands across managed and intact forest lands	<\$20 ha^{-1} (Bronson W Griscom *et al.* 2017; Arneth *et al.* 2019) (global estimate)	Costs of fuel management and prescribed burns. Costs of implementing fire management plans with many groups of stakeholders (Stephens *et al.* 2013).	• Avoids forest degradation and deforestation. • Prevents biodiversity and species loss. • Protects local livelihoods and cultural values.	>5.8 million people affected by wildfire globally; max. 0.5 million deaths per year by smoke globally (medium confidence) (Johnston *et al.* 2012; Doerr and Santín 2016; Smith *et al.* 2019) (global estimate)
4. Forest management strategies to restore the productive capacity of forest ecosystems							
Increased mortality due to climate stresses	Assisted natural regeneration in degraded forest landscapes	Forest landscape restoration positively affects the structure and function of degraded ecosystems (Shimamoto *et al.* 2018). Forest restoration may enhance connectivity between forest areas and help conserve biodiversity hotspots (Locatelli *et al.* 2015a; Ellison *et al.* 2017; Dooley and Kartha 2018). Forest restoration may improve ecosystem functionality and services, provide microclimatic regulation for people and crops, wood and fodder as safety nets, soil erosion protection	Tree regeneration takes place in more degraded lands across different types of tenure regimes in public, community and private lands	Assisted natural regeneration 180-980 (USD ha^{-1} (in USD 2019) (Cury and Carvalho 2011; Lira *et al.* 2012; MMA 2017; Silva and Nunes 2017)	Opportunity costs of alternative land uses, costs of maintaining regenerating landscapes (e.g. exclusion plots), costs of facilitated dispersal or seeding (Naidoo and Adamowicz 2006).	• Uses microclimatic changes from regeneration to create emergent landscape restoration from available and present species in soil seed banks or dispersive capacity of local habitat patches. • Increases potential area and influence of forest ecosystems even into marginal matrix habitat (Chazdon and Guariguata 2016).	The benefits of regeneration of degraded landscapes has the potential to impact the lives of >25 million people globally (Medium confidence) (Reyer *et al.* 2009; UNISDR and CRED 2015; Sonntag *et al.* 2016; Bronson W Griscom *et al.* 2017; Smith *et al.* 2019) (global estimate)

		and soil fertility enhancement (Locatelli *et al.* 2015a). Land restoration can reduce future risks (e.g. by protecting against hazards) and current vulnerability (e.g. by diversifying livelihoods) (Pramova *et al.* 2019). Natural forest regeneration contributes to climate mitigation through carbon removals (Lewis *et al.* 2019), and this would imply less need for climate adaptation					
Changes in the frequency and severity of forest disturbance	Expand agroforestry systems (AFs) in buffer zones and mosaic landscapes	Agroforestry reduces pressure on intact forests and can enhance ecosystem services at the landscape level (Jose 2009). It can also help to increase resilience to pests and diseases through ecological processes (Miccolis *et al.* 2016). Agroforestry can reduce vulnerability to hazards like wind and drought, particularly for subsistence farmers (Thorlakson and Neufeldt 2012).	Agroforestry has a large potential in collective forest lands, both managed and degraded	7150-22575 USD ha^{-1} (n USD 2019) (Raes *et al.* 2017; Nello *et al.* 2019)	Opportunity costs of other land uses. Costs of engaging in markets and/or developing markets for agroforestry products. Risks of market saturation and supply/demand inconsistencies. (Torres *et al.* 2010; Mercer *et al.* 2014)	Biodiversity (habitat, migratory corridors, gene flow) Soil structure and fertility, nutrient cycling Water infiltration/ water recharge, erosion control Buffer strips can reduce the resource pressures on native ecosystems by providing income and resources for people (Vieira *et al.* 2009).	Potential to improve farmers' livelihoods and quality of life of 2,300 million people globally (medium confidence) (Lasco *et al.* 2014; Smith *et al.* 2019) (global estimate)

Table Notes:
This table draws on Appendix 6.1-6.4 from Seppala et al. 2009, pp. 71-77
(1) Agricultural expansion is the major driver of deforestation in developing countries. Cost of reducing deforestation is based on opportunity cost of not growing the most common crop in developing countries (Maize) for six years to reach tree maturity, with yield of 8 t ha^{-1} (high); 5 tons ha^{-1} (medium) & 1.5 t ha^{-1} & price of USD 329 t^{-1}. Also, reduced deforestation practices have relatively moderate costs, but they require transaction and administration costs (Kindermann *et al.* 2008; Overmars *et al.* 2014).
(2) May not deal with displacement of wild species due to climate change
(3) Fragments of disconnected HCVAs have less value to preserve ecological services
(4) Forest management strategies may decrease stand-level structural complexity and may make forest ecosystems more susceptive to natural disasters like wind throws, fires, and diseases (Seidl *et al.* 2017)

[START BOX CCP7.2 HERE]

Box CCP7.2 Contribution of sustainable tropical forest management to the SDGs

There is increasing evidence of positive impacts of resilient tropical forests, biodiversity, and sustainable forest management in achieving SDGs as illustrated in Table Box CCP72.1. However, there is also risk of unintended consequences based on conflicts between the use of forest-based goods and services and effects on tropical forest resilience, ecosystem services, and biodiversity (Baumgartner 2019). For instance, substitution of fossil fuels and non-renewable resources with bio-based products can lead to deforestation and the loss of biodiversity (Carrasco 2017) (Cross-Working-Group Box BIOECONOMY in Chapter 5). Deforestation as a result of increased agricultural production and productivity could hamper efforts in addressing long term food security, particularly for forest dependent people (Newton et al. 2016); CCP7.2.3). Synergies and trade-offs depend very much on local contexts and are therefore presented in exemplary form.

IFAD (2016) estimated that there are 640 million people living below the poverty line in rural areas of 43 tropical countries. Poor communities rely on ecosystem services for their subsistence livelihoods, and often they have limited capacity to adapt to change, making them more vulnerable to climate change and other forms of changes (Bhatta 2015). Managing forests sustainably benefits both urban and rural communities, including provision of food and fiber, on watershed hydrology, agroforestry production, among others (Powell et al. 2013; Dawson et al. 2014) (Clark and Nicholas 2013) (Mbow et al. 2014)) (Table Box CCP7.2.1).

Table Box CCP7.2.1: Examples from sustainable tropical forest management (STFM) in achieving SDGs.

SDGs	Contribution of STFM to the Goals	Adaptation Interventions	Supporting references
1 No Poverty	Area of forest land with legal property status held by communities	In Mexico, community forest management (CFM) has played a pivotal role in forest cover and biodiversity conservation in the region where timber production and processing generates income and thereby offers a way out of poverty for families in communities with rights to forests.	(Ellis et al. 2015)
	Improve incomes through selling forest products or by generating employment for the poorest	Non-timber forest products (NTFPs) are a significant source for socio-economic, employment and income generation, particularly for tribal people.	(Kumar 2015)
	Improve income through valuation of ecosystem services	In Cambodia, contribution of forest resources should be integrated into payment for ecosystem services schemes, in order to provide more diversified income streams, insulating indigenous people from shocks and stressors.	(Nhem 2018)
2 Zero Hunger	Forests also provide food, which improves food security and nutrition	In Cameroon, forest fruits provide important macro- and micronutrients lacking from the family diets of rural people. Association between tree cover and the dietary diversity of children in the communities of 21 countries across Africa.	(Fungo et al. 2015) ; (Ickowitz et al. 2014)
3 Good Health & Wellbeing	Medicinal plants contribute to emotional and spiritual wellbeing	Medicinal plants and the associated Bhutanese traditional medicine (BTM) are protected by the country's constitution and receive both government support and acceptance by the wider public. These medicinal plants have been one of the drivers of the 'Gross National Happiness (GNH)' and biodiscovery projects in Bhutan.	(Wangchuk and Tobgay 2015)

	Health co-benefits of preserving biodiversity	In the Brazilian Amazon, interventions targeted specifically at preserving biodiversity in protected areas generate health co-benefits. From the perspectives of malaria, acute respiratory infection (ARI), and diarrhea, results suggest that the public health benefits of strict PAs may offset some of their local costs. Nature is doing its part by providing a form of (human) capital for the rural poor and the politically voiceless.	(Bauch et al. 2015)
4 Quality Education	Inclusive education that builds and reinforces positive attitudes to forest	Encouraging and enabling pro-forest behavior as well as strengthening education systems that respect, nurture and enable Indigenous knowledge and local knowledge.	(Kanowski 2019) (Tengö 2017) (Vaidyanathan 2014)
		The value of social capital for maintaining sustainability of community forest management includes, among others, individual characteristics, procedural knowledge and access to information. Initiatives to manage natural resources are *likely* to be more successful if the forest management program initiators consider several factors that influence the capacity development of resource users.	(Lee 2017)
5 Gender Equality	Within genders, other characteristics such as class, race, caste, culture, wealth, age and ethnicity influence responses and affect the impact of climate variability and change on livelihoods	Despite challenges, Nepal's community forestry policy is considered one of the most progressive, as it allows women to exercise equal rights with men in the management and utilization of community forests. Furthermore, women-only forestry groups have registered many success stories.	(Lama et al. 2017); (Agarwal 2015)
6 (Clean Water & Sanitation)	Regulate water supply, water quality and water purification	Evidence from the Hindu Kush Himalayas require improved upstream-downstream integration, transboundary cooperation and greater coordination of implementation of different SDGs. Greater efforts are required to make the communities struggling on the frontline of sustainable forest management more climate resilient. Forest concessions can make a positive contribution to this by minimizing the negative impacts of harvesting operations on water access and by employing appropriate restoration techniques as required by the concession contract and national legislation.	(Scott C.A. 2019); (Amezaga 2019) (Bruggeman et al. 2015),
7 (Affordable & clean energy)	Energy transitions	Decreased reliance on traditional wood fuels and increased use of forest-derived modern fuels (e.g. biofuel) are generally synergistic with achieving other SDGs, such as livelihoods strategies. However, modern wood fuels need improved stoves to ensure the energy is clean.	(Jagger 2019) ; (Simangunsong et al. 2017)

8 (Decent work and economic growth)	Stimulating economic growth and minimizing forest loss	Synergy potentials exist where growth strategies and associated policies target the forest section with NTFPs from natural forests, ecotourism and payments for environmental services.	(Stoian 2019)
		Community forestry enterprises have the potential to make significant contributions by providing a solid institutional framework to efficiently translate SDGs into actions. It also improves forest management, social cohesion and rural incomes amongst local communities in developing countries.	(Aryal 2020); (Vázquez-Maguirre 2020); (Baynes 2015)
9 (Industry innovation & infrastructure)	Integration of small-scale business into value chains and markets	Strategies in relation to sustainable supply chains and tropical forest protection, i.e. Unilever and Instituto Centro de Vida (ICV), demonstrate both alignment and variability between and within organizations. Associated incentives could help balance the burden of responsibility for implementation between global and local actors of promoting zero deforestation.	(Delabre et al. 2020)
10 (Reduced Inequalities)	Reduction in the number of poor households	Results from Waseda-Bridgestone Initiative for Development of Global Environment (W-BRIDGE Initiative) in South Kalimantan province through capacity building delivered by academic partners. This initiative also increased land area ownership from 0.28 to 1.23 ha per household.	(Hiratsuka 2019)
	Protect the workers and communities long-term and economic well-being	Rural agrarian communities in low-latitude tropical forests (e.g., communities in Southeast Asia, South America, Central Africa) adapting to chronically hotter temperatures in common ways, such as adjusting when and how they work. Decision-makers should develop an understanding of these behavioral adaptations that are already being adopted before establishing broader adaptation strategies.	(Masuda 2019)
11 (Sustainable Cities and Communities)	Upstream forests influence water supplies to cities	Watershed condition is associated with measurable health outcomes downstream. Maintaining natural capitals within watersheds is an important public health investment especially for populations with low levels of built capital.	(Herrera et al. 2017)
		Evidence from Marikina Watershed Integrated Resources Development Alliance in the Philippines working together with all stakeholders to restore Marikina Watershed to reduce disaster risk and urban resilience.	(Devisscher 2019)
		Synergies delivered through sound urban forestry approaches could benefit not only urban dwellers but also forest communities. Community groups have also taken responsibility for urban forestry in the absence of strong government commitment.	(Konijnendijk 2018)
12 (Responsible Consumption & Production)	Generates materials for sustainable consumption	Forest concessionaires can also increase the repurposing of waste to improve sustainable consumption. For instance, the logging company Congolaise Industrielle des Bois produces electricity from sawmill wood waste.	(Tegegne et al. 2019)

13 (Climate Action)	Enhance resilience and adaptive capacities to climate change through forest management	Mixed agroforestry systems offer opportunities to simultaneously meet the water, food, energy and income needs of densely populated rural and peri-urban areas in Indonesia.	(van Noordwijk et al. 2016)
	Carbon-based conservation	Payment for carbon-based conservation (eg. REDD+, Green Climate Fund) protecting peatlands from avoidable human impacts for favourable return from carbon conservation investments.	(Roucoux et al. 2017)
		REDD+ has mixed impacts on communities' socio-ecological resilience. On one hand, increases in network ties and participation in decision-making would enhance potential for local adaptability. However, restrictions on local forest practices could limit communities' ability to manage uncertainty.	(Hajjar 2021)
14 (Life Below Water)	Support numerous ecosystem services	Complex root systems serve as shelter as they protect juvenile fish from predators as well as provide food and nutrients for fish.	(Friess 2019)
		Mangroves contribute to fisheries production and have become one of the higher carbon stocks compared to other forests. The mangroves system of the Zambezi River Delta, Mozambique confirms the consistency of substantial C stocks typical of mangroves across a relatively large and hydrologically diverse area.	(Stringer 2015)
	Protection for aquatic macroinvertebrates habitats	The riparian canopy of the tropical forest is significantly able to maintain in-stream temperature that is important to aquatic macroinvertebrates. The study of Gunung Tebu, Malaysia showed high diversity and abundance of steams invertebrates as the natural habitats are minimally impacted.	(Md rai 2014)
15 (Life on Land)	Community monitoring of their own forests or forest within communal jurisdiction, sustainable certification	Mainstreaming SFM in vast tracts of forest, thereby increasing the share of forest area under a forest management plan, including the proportion of forest area certified under independent forest certification schemes.	(van Hensbergen 2016)
		Even with tension between the management of resources for local goals and the need for public good values, still there are some communities that maintain strong control over their lands and resources in achieving desirable conservation outcomes and willing to see large tracts of land set aside, i.e. areas held to be sacred.	(Sayer et al. 2015); (Sheil 2015)
16 (Peace, justice and strong institutions)	Addressing complexity of implementing conservation policy	Target 16.7 calls for responsive, inclusive participatory and representative decision-making at all levels. Decentralization in forest governance observed through community-based/collaborative forest management depends on the strength of underlying land tenure and use rights, as well as capacity to benefit from those rights.	(Baynes 2015) ; (McDermott 2019) ;(Myers 2017) ;(Nunan 2018)
		By 2021, Thailand plans to increase use of renewable and alternative energy by 25% including energy crops. Adequate forest protection is critical, as increasing demand for energy crops may drive demand for expanding agricultural production into	(Phumee 2018)

		public forests, benefitting some SDGs and threatening others.	
	Modern technologies in forest management control	Technologies including remote sensing and Geographic Information System (GIS) are interrelated as they support management actions in global forest resources management thus reducing exploitation through monitoring and evaluation activities.	(Beckline 2017)
	Governance laws and policies provide access to justice for all	The Forest Stewardship Council (FSC) and the program for the Endorsement of Forest Certification (PEFC) significantly contribute to ensuring the legality of the timber supply chain. The (FAO 2018b) considers the proportion of forest with secure tenure rights for forest dependent people and the local community in ensuring equal rights to economic resources for all.	(Gabay 2019)
17(Partnership for the goals)	Co-benefits derived from tropical forest conservation	Raising awareness of the interconnectedness of tropical forests and the SDGs through multi-disciplinary collaboration will support more informed decisions of social, cultural, economic and policy interest.	(Swamy 2018) ; (Bukoski et al. 2018)
	Voluntary Partnership Agreements (VPAs) stabilize and reproduce the very forest governance regime	In Ghana, the adoption of the VPA resulted in an improved Timber Legality Assurance System (TLAS), strengthened Social Responsibility Agreements (SRA) enforcement, updated forest management plans, artisanal milling strategies and technical transparent timber dights allocations.	(Hansen 2018)
	Central bureaucracies promote forest benefits: countering conservation	Forest Management Units (FMUs) could be utilized to support conservation-oriented regimes with worldwide interests as well as domestic production-oriented regimes. For example, FMUs might potentially link up with global and domestic timber certification regimes under the Multistakeholder Forestry Programme (MFP3) imitative.	(Sahide 2016)

[END BOX CCP7.2 HERE]

CCP7.6 Governance of tropical forests for resilience and adaptation to climate change

Deforestation and forest degradation in tropical forests has grown in prominence as priorities for environmental governance in the face of climate change, given the large share of forest and land use GHG emissions in the national profiles of tropical forest countries (*high confidence*) (Butt et al. 2015; IPCC 2019). This is reflected in Parties' Nationally Determined Contributions to the Paris Climate Agreement (UNFCCC 2021). Significant investments in REDD+ readiness, improved forest monitoring, assessments of drivers of deforestation and, forest degradation and related policy responses, and stakeholder engagement have occurred over the past decade in countries across Africa, Asia-Pacific, and Latin America and the Caribbean (Hein et al. 2018; UN-REDD Programme 2018; World Bank 2018). Fifty three percent of countries use highest quality remote sensing data for forest monitoring and reporting, covering 93% of forest cover (Nesha et al. 2021). However, improved monitoring has not yet translated into forest governance effectiveness. Since the New York Declaration on Forests was endorsed in 2014, average annual humid tropical primary forest loss has accelerated by 44% (NYDF 2019). Policy responses towards conservation and ecosystem resilience are found to be insufficient to stem the direct and indirect drivers of nature deterioration (*high confidence*) (IPBES 2019). For governance measures to be effective, it is necessary to alter the direct and underlying drivers that are leading to forest destruction or impeding the implementation of sustainable forest management practices and actions to restore degraded forests (*high confidence*) (CCP7.2.3; CCP7.5; UNFCCC, 2013).

Private sector commitments to reduce deforestation impacts in their commodity supply chains are growing, but evidence of impact is slim and inconclusive (Garrett et al. 2019; NYDF 2019). Half of the biodiversity loss associated with consumption in developed economies occurs outside their territorial boundaries (Wilting et al. 2017), and trends in international trade in land-based production systems are increasing, with greatest impacts on tropical forests (Nyström et al. 2019; Hoang and Kanemoto 2021). In addition, in some cases the impacts of financialization (e.g. correlation of commodity prices with stock market dynamics rather than pure demand) are found to be larger than those related to timber and agricultural commodity production dynamics (Girardi 2015; Ouyang and Zhang 2020); cross-reference to Chapter-5.13). Such factors present challenges for governance and policy responses.

The complexity of tackling drivers of forest loss and degradation will increase as climate impacts on forests and ecosystems intensify in the context of incomplete information and limited understanding of risks (Helbing 2013; Hughes et al. 2013; Springmann et al. 2018; Tu et al. 2019), necessitating novel approaches to forest governance for resilience (Keenan 2015; Spathelf et al. 2018). Therefore, governance—defined as efforts that seek to influence the relationship between existing social processes and governance arrangements by using regulatory processes, mechanisms, and organizations (Agrawal et al. 2018) is a crucial process to convene stakeholders for decisions (FAO 2018a).

This section describes seven levers that support transformative environmental governance towards resilience of tropical forests by tackling the underlying indirect drivers, offering policy solutions and governance challenges and opportunities. The first five build on IPBES (2019) whereas the remaining two are drawn from the governance literature as highly relevant variables specific to the tropical forest context due to their prominence in the international frameworks developed over the past ten years (Table CCP7.5). Monitoring and finance are embedded in multiple levers. The levers include:

1) developing incentives and increased capacity for environmental responsibility (particularly in relation to global targets such as the SDGs, Aichi Biodiversity Targets and the Paris Agreement) and discontinuing harmful subsidies and disincentives;
2) reforming sectoral and segmented decision-making to promote integration across sectors and jurisdictions to mainstream environmental objectives across institutions within and among all relevant sectors;
3) pursuing pre-emptive and precautionary actions in regulatory and management institutions and businesses to avoid, mitigate and remedy the deterioration of nature, and monitor outcomes;
4) managing for resilient social and ecological systems in the face of uncertainty and complexity;
5) strengthening environmental laws and policies and their implementation, and the rule of law more generally (Pörtner et al. 2021);
6) acknowledging land tenure and rights to recognize the need of bringing human rights considerations into the climate change regime; and,
7) enhancing inclusive stakeholder participation to ensure effective, efficient and equitable outcomes (Pasgaard et al. 2016).

While the first five levers are relevant to environmental governance more broadly, the exploration of these levers in Table CCP7.5 is more specific to governance for forest resilience, drawing upon insights related to each transformation lever. Next to the governance solutions being implemented currently, indications of future challenges/opportunities related to resilience in tropical forests are explored based on examples from the recent literature.

Table CCP7.5: Levers of transformative change to tackle the underlying indirect drivers of forest deterioration for resilience.

Levers of transformative change	Barriers	Current governance and policy solutions and potential future challenges and opportunities with an orientation towards resilience in tropical forests
1. Incentives and capacity-building	• Population growth and corruption counteract governance effects (Enrici and Hubacek 2016; Busch and Ferretti-Gallon 2020; Fischer et al. 2020) • Macroeconomic development favoured over ecosystem service provision-environment ministries under resourced and politically weak compared to those for economic and natural resource development (UNEP 2019) • Though food systems are the major driver, many interconnected food system activities and effects do not have established governance regimes to address them (Clapp and Scott 2018). • Reliance on non-state market-based approaches (e.g. zero-net deforestation) has not achieved necessary impact against stated targets, reporting is lacking (Lambin et al. 2018; Global Canopy 2019) • Finance for forest mitigation is less than 1.5% of total since 2010 (Partners 2019), and amount for forest adaptation is even less (Micale et al. 2018)	**Current policy solutions** • REDD+ and Payments for ecosystem services (PES) • Corporate supply chain commitments (WWF and BCG 2021) • Product certification and forest certification have mixed results in addressing deforestation (Blackman et al. 2018; van der Ven et al. 2018) • Agricultural credit restrictions (Assunção et al. 2020) • Protected areas and area-based conservation measures (OECMs) (Maxwell et al. 2020) • Clear performance indicators and monitoring systems to assess performance (Agrawal et al. 2018) **Future policy challenges/opportunities** • Policies that insulate the forest frontier from the influence of high commodity prices (Busch and Ferretti-Gallon 2020) • Project-level biodiversity responses linked to broader jurisdictional biodiversity targets (Simmonds et al. 2020) • Ecological fiscal transfers to base portions of intergovernmental fiscal transfers on ecological indicators (Busch et al. 2021) • Financial disclosure on risks, divestiture, environment-related investment mandates (Halvorssen 2021) • Identification of means for the forest-based bioeconomy (wood fuel, timber) to be sustained (Dieterle and Karsenty 2020) • Incentives towards less emissions-intensive inputs in manufactured products, such as bamboo (van der Lugt et al. 2018) • Reducing imports of embedded deforestation (role of land-use telecoupling) (Gardner et al. 2019) • Supply chain traceability and public reporting (Gardner et al. 2019; Global Canopy 2019)
2. Cross-sectoral cooperation	• Inherent vertical and horizontal fragmentation of policy arena • Challenge of silos between ministries (Nilsson et al. 2016) • Policy integration has a stronger chance of reforming existing policies and competing sectors than coordination, but is challenged to overcome sectoral fragmentation and reach international actors and markets (Kissinger et al. 2021)	**Current policy solutions** • Policy coordination and integration (Candel and Biesbroek 2016) • Jurisdictional and landscape approaches in targeted regions and commodity sectors/supply chains (Reed et al. 2017; von Essen and Lambin 2021) **Future policy challenges/opportunities** • Theories of change applied and testing of policy effectiveness (Meehan et al. 2019; Bager et al. 2021) • Whole-of-government approaches to change mandates across ministries • Mainstreaming climate change into sectoral policies (Di Gregorio et al. 2017)

		• Policy mixes implemented as a bundle, policy instrument selection attuned to complexity of the problem (Henstra 2015; Head 2018)
3. Pre-emptive action	• Complexity of the issues for any specific level of jurisdiction to grapple with, scale mismatches (temporal, spatial and institutional), institutional inertia (Bai et al. 2016) • Reliance on path dependency rather than innovation (Beland Lindahl et al. 2017; Peters et al. 2018; Wieczorek 2018) • Agenda setting and framing influences political and policy responses (Soto Golcher et al. 2018) • Problem denial and blame avoidance on the part of decision-makers (Howlett and Kemmerling 2017).	**Current policy solutions** • GHG emission cap-and-trade systems and carbon pricing (Green 2021) • Moratoria • Identifying thresholds of concern, when critical thresholds of fast-changing variables are triggered, and nonlinear responses erode the resilience of ecosystems (such as in the case of changing forest fire regimes) (Gillson et al. 2019) • Reduce loss and waste of biomass • Change in consumption patterns, sharing and reuse • Shareholder divestiture due to climate/forest and biodiversity risk (Halvorssen 2021)
4. Decision-making in the context of resilience and uncertainty	• Scope of problem identification limited (Beland Lindahl et al. 2017) • Increasingly complex and networked world increases risks, but reduces our ability to understand and manage these risks (Helbing 2013; Tu et al. 2019)	**Current policy solutions** • Forecasting, scenarios of future climate and forest condition, socio-economic dimensions, science-policy dialogue (Bele et al. 2015) and thresholds for ecosystem shifts due to mortality (tipping points) (Verbesselt et al. 2016). **Future policy challenges/opportunities** • Interdisciplinary and transdisciplinary approaches to data gathering and policy design (Keenan 2015) • 'Robust' decision-making approaches for adaptive forest management (Hörl et al. 2020) • Maintain diversity and redundancy, manage connectivity, and slow variables and feedbacks (Biggs et al. 2012) • Measurement and disclosure of climate and ecosystem risk (NBIM 2021)
5. Environmental law and implementation	• 69% of agricultural conversion of tropical forests *likely* illegal between 2013-2019 (Dummett et al. 2021) • 90% of countries (of 31 assessed), identify weak forest sector governance and institutions, conflicting policies beyond the forest sector, and illegal activity main underlying drivers (Kissinger et al. 2012); corruption and illegality are identified as key factors in increasing forest loss (Piabuo et al. 2021). • Implementation and enforcement of environmental laws falls far short; primary obstacle is political will (UNEP 2019)	**Current policy solutions** • Environmental laws and regulations (Head 2018) • Trained prosecutors • Citizen rights to information (Bizzo and Michener 2017) **Future policy challenges/opportunities** • Capacity and willingness to engage iterative processes for continuous effort in transparency and accountability (in implementing the Extractive Industry Transparency Initiative)(Lujala 2018) • Regulatory frameworks as enablers to motivate and hold private sector initiatives to account (test effectiveness) (Begemann et al. 2021) • Nested and multilevel governance arrangements (Ravikumar et al. 2015) • Diagnosing the political drivers of decision making through political economy assessment (Fritz et al. 2014)

	• Conflicting legal instruments, lack of clarity in implementation, monitoring and evaluation, responsibilities are poorly defined and fragmented across multiple agencies (Ranabhat et al. 2018) • Lack of sanctions, transparency and accountability (Bai et al. 2016; Enrici and Hubacek 2016) • Open-ended decision-making exacerbates political asymmetries (Holley and Sofronova 2017)	
6. Lend tenure/rights	• Though recognition of indigenous self-determination is growing, many cases of legal recognition still lack full authority to govern (UN-DESA 2021) • Free Prior Informed Consent (FPIC)	**Current policy solutions** • Legal and constitutional recognition of rights, collective/communal rights (Safitri 2015; Blackman et al. 2017; Gebara 2018) • Indigenous land demarcation (Baragwanath and Bayi 2020). • Community-based forest management (Pelletier et al. 2016) **Future policy challenges/opportunities** • Forest protection /climate and biodiversity is strongest when indigenous people hold collective legal titles to their lands (IPCC 2019) (In Latin America, deforestation rates are about 50% lower in Indigenous territories than in other forested areas) (FAO and FILAC 2021).
7. Participation and stakeholder inclusion	• Governments increasingly rely on highly autonomous semi-public or private organizations for policy results, which weakens control of the process (Howlett et al. 2015), yet mediating between diverse values and interests of citizens, consumers, business, community is a determinant of policy effectiveness (Peters et al. 2018). • Growing legal restrictions on civil society involvement in governance and access to funding (UNEP 2019) • Institutional practices of stakeholder consultation in REDD+ not well operationalized (criteria and transparency often lacking) (Fujisaki et al. 2016)	**Current policy solutions** • Multistakeholder dialogue combined with moratoria (e.g. Brazilian soy moratorium) (Gibbs et al. 2015) • Community-based monitoring (Slough et al. 2021) **Future policy challenges/opportunities** • Collaborative networks (Thomas et al. 2018) • Re-evaluating agency, social structures and the distribution of power to uphold rights (I. Delabre et al.) • Community engagement correlated to secure rights to resources (Pham et al. 2015)

[START FAQ CCP7.1 HERE]

FAQ CCP7.1: How is climate change affecting tropical forests and what can we do to protect and increase their resilience?

Global warming, droughts, extreme rainfalls, and sea-level rise cause significant impacts on tropical forests.

In addition to climate change, tropical forests are experiencing non-climatic stressors. Conversion of forest into large scale agriculture land and exploitation of timber and non-timber forest products are increasing pressure and amplifying the impacts of climate change on the remaining areas of tropical forests. These include biodiversity decline, increases of fires, large scale ecosystem transformation, e.g., into savannah in South Eastern Amazon, and increasing carbon emissions due to deforestation, forest conversion and forest degradation. Further, loss of forest resources leads to the decline of livelihoods of Indigenous Peoples and local communities. All nations need to collaborate to implement collective actions to protect tropical forests.

Tropical forests are essentially important for the health of planet Earth. Tropical forests in Asia, Africa, and South America regulate carbon, water, and chemical cycles, which maintain a healthy climate and nutrient cycles for supporting life. Tropical forests are home to two-thirds of our world's biodiversity, although they cover only about 13 percent of the land on Earth but it is not exactly known how many millions of living creatures, such as microorganisms, insects, amphibians, snakes, fish, birds, mammals, and primates, live in tropical forests.

Approximately 1.3 billion people directly depend upon tropical forest resources to survive. Others are indirectly dependent upon the health and provisioning of ecosystem services and goods from tropical forests. The forests provide many kinds of economic products, such as timber, medicines, and food, recreational services, such as nature trekking, bird and wildlife watching, to mention a few. Indigenous People and other forest-dependent communities have shown extraordinary knowledge on how to manage forest resources to meet their subsistence needs without causing forest degradation. This forest culture and wisdom are broken when the rate of forest extraction changes into unplanned and unsustainable large-scale transformation.

Deforestation and land-use changes in tropical forests cause not only physical and biological changes on flora and fauna but also rapid changes in cultures harming forest peoples. A degraded tropical forest is prone and more vulnerable to climate change. An increase in temperature in lowlands creates an unfavorable condition for optimum growths of many kinds of plant species, which affects, as well, several agricultural plants. Coffee farmers, for example, are forced to open new forest frontiers in highland areas to meet an optimum temperature for the growth of coffee.

The onset and duration of dry and rainy seasons also changes. A prolonged wet season has excessive rains, which causes flash floods and substantially disturbs a fruiting cycle of many plant species. Due to high rainfall and high humidity, most flowers of forest trees fail to mature, and hence essentially deplete fruit production. Most trees in tropical forests require a short period of a dry season in order to have a mass fruiting season. On the other hand, a prolonged dry season causes soils to dry in deeper layers, higher atmospheric demand for water vapor and enhanced forest fires. In the tropical humid forests, the majority of forest fires are anthropogenic. In Southeast Asia, peat fires cause large carbon emissions and haze pollution, which harms locals and people in neighboring countries. The impact on tropical forest comes also from the rise of sea level rise which due to changes in salinity and sedimentation rates, and the expansion of inundated areas leads to the decline of mangrove productivity.

Projected impacts of climate change on the tropical forest might be detrimental to safeguards of local communities and a significant number of flora and fauna in the tropics. In South-Eastern Amazon, reduction in precipitation, due to changes in the climate pattern, associated with intense deforestation and land cover change are leading to reduction of productivity in the remaining forest areas, and might lead to a large-scale change in the forest structure, which can become a savannah. In Southeast Asia, in particular in Indonesia and Malaysia, prolonged dry seasons associated with the El Niño phenomenon cause extensive peat fires, releasing large amounts of carbon dioxide, and creating various health problems related to haze pollution. Furthermore, climate change interacts with deforestation for agriculture (crops, livestock and plantation forestry), logging, mining or infrastructure development exacerbating temperature and rainfall changes resulting in more degradation.

Climate change together with forest fragmentation and deforestation also harms wildlife. For example, the orangutan, an endemic species to tropical peat forests in Kalimantan and Sumatra, is classified as critically endangered. Many other endemic and unknown species of flora in tropical forests are in the same condition, and could experience a mass extinction at a more rapid rate than the previous five mass extinctions on Earth. About 1.3 million Indigenous Peoples depending on the natural resources of the tropical forest would suffer from cultural disruption and livelihood change due to forest loss.

To protect tropical forests a collective action of all nations is needed. It requires a global effort to stop deforestation and the conversion of tropical forests. The role of Indigenous Peoples and local communities as forest keepers must be strengthened. Economic incentives for protecting tropical forests, among other strategies, could facilitate collective actions towards a sustainable management of tropical forests. Sustainable, effective and just strategies to increase the resilience of tropical forests need to consider the complex political, social and economic dynamics involved, including the goals, identity and livelihood priorities of Indigenous Peoples and local communities beyond natural resource management. Strategies can benefit from integrating knowledge and know-how from traditional cultures, fostering transitions towards more sustainable systems.

[END FAQ CCP7.1 HERE]

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