CCP7

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 among 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 heatwaves, 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 fertilisation, 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 degradation or savannisation 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 confidenc*e). {CCP7.5; Box CCP7.1}

Community-based adaptation, built on Indigenous knowledge and local knowledge (IK and 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 often 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}

Governance responses to addressing the direct and underlying drivers of deforestation have been inadequate to reduce pressures, yet the urgency 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: incentivising 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}

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.

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 increases 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 among 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 minimising 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 utilised, 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 is property rights and tenure arrangements allowing stewards of the land, including Indigenous Peoples, securing long-term access and utilisation of forest resources (*medium confidence*) (Rahman and Alam, 2016; Naughton-Treves, 2014).

Figure CCP7.1 illustrates the interconnections of climate risks and non-climate drivers facing tropical forests. On the one hand, the rates and extent of deforestation and forest degradation result in loss of ecosystem services, biodiversity and human well-being and enhance the vulnerability of the social-ecological system to the impacts of climate change. On the other, forest protection and sustainable forest management result in higher resilience of the ecosystem against climate impacts. This framing illustrates both the complexity and scale of the challenge and provides opportunities to reduce impacts at different scales by eliminating the underlying drivers, both climate and non-climate related, through policies and measures at global, national and subnational levels, involving state and non-state actors alike.

Building on what has been presented in IPCC AR5, SR15 and SRCCL, Section CCP7.2 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 CCP7.3 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 CCP7.4 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 CCP7.5 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 CCP7.6, 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, 2019a).

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 data set (ESA, 2017). The ESA data set provides a direct mapping to IPCC land categories (e.g., 'forest'), allowing for standardised and consistent reporting of existing forest and forest gain/loss in each ecological zone. The most extensive tropical ecological zone is the tropical rainforest (1459 Mha or about 25% of all tropical ecological zones), followed by tropical desert (which is not further considered here), tropical moist

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.

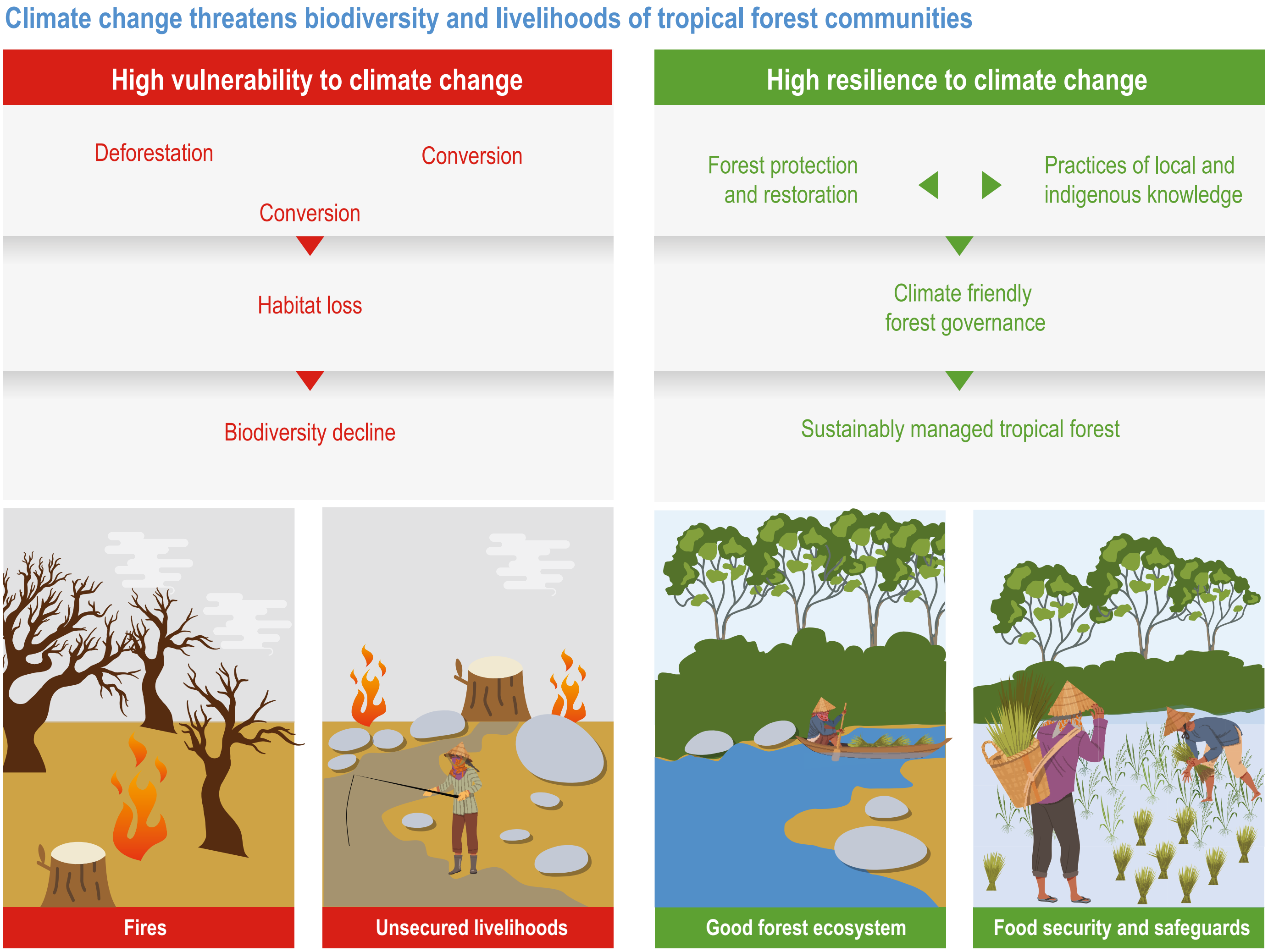

Figure CCP7.1 | Impacts of climate change and human disturbances on tropical forests lead to high risk of biodiversity loss and uncertainty of livelihoods for the majority of forest-dependent communities (left side). Good forest governance would increase the resilience of tropical forest through better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

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 Southeast Asia, and is the most intact tropical forest biome (Table CCP7.1). Significant portions of tropical moist forest, which abut 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 to 645 Mha (Pan et al., 2013; Bastin et al., 2017; Ocón et al., 2021).

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 harbour 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, Maia and Mourão, 2016).

Rates of global biodiversity loss in the past few decades have acelerated to levels that are, for some taxa, approaching the estimated rate of

Tropical ecological zones as defined by the FAO

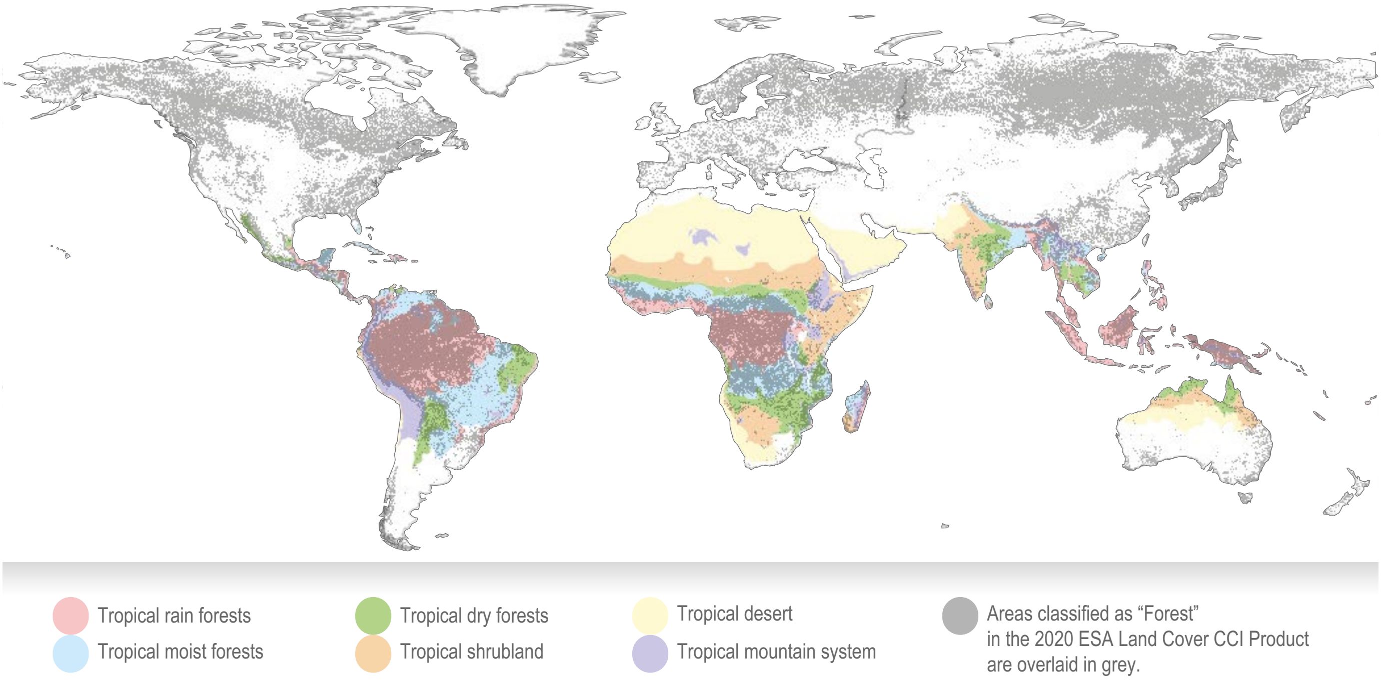

Figure CCP7.2 | Colours represent tropical ecological zones as defined by the FAO (FAO, 2012). Areas classified as 'forest' in the 2020 ESA Land Cover CCI Product (ESA, 2017) are overlaid in grey.

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**

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 because of 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 with 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*).

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

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

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

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 (Table CPP7.2).

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; 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 greenhouse gas (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 catalyses 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).

Forest degradation is more difficult to track, but can have large negative effects on carbon storage, provision of ecosystem services, and biodiversity (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].

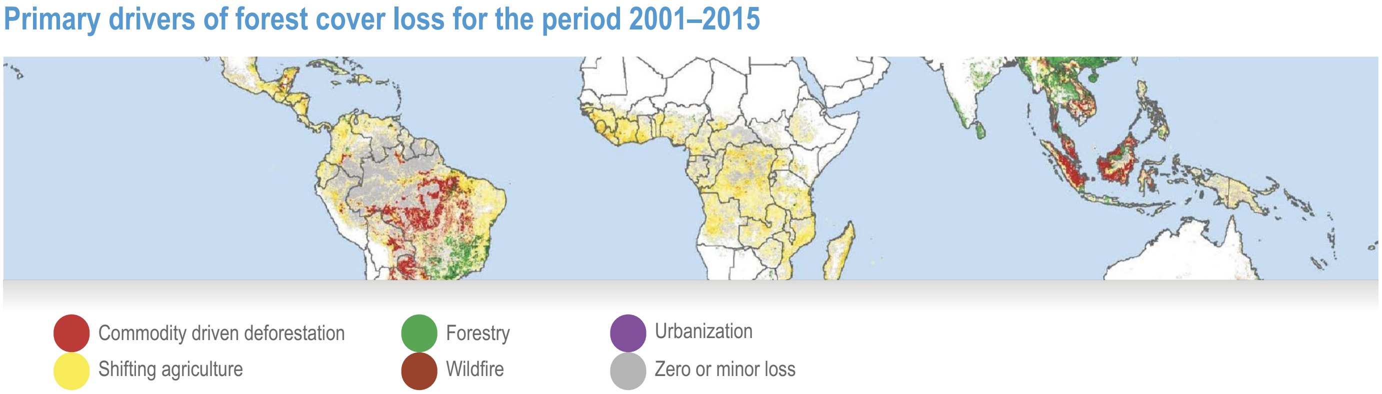

Figure CCP7.3 | Primary drivers of tropical forest cover loss for the period 2001–2015. Darker colour intensity indicates greater total quantity of forest cover loss. While some tropical forest cover loss is temporary, a large portion is related to deforestation. Source: Curtis et al. (2018). Cropped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

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) [WGII 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, as well as 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 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 and 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 with 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 fertilisation effect [Box 2.3 in IPCC 2019b]. Observed changes in the terrestrial carbon sink and process-based vegetation models indicate that tropical vegetation response to CO_2 fertilisation (Schimel et al., 2015) is combined with other factors such as nitrogen deposition and length of the growing season, while aerosol-induced cooling may also have played a role in enhancing the carbon sink [Box 2.3 in IPCC 2019b]. Contrastingly, evidence for CO_2 fertilisation 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, that is, the amount of carbon assimilated as biomass per unit of water used, increases under elevated atmospheric CO_2 levels owing 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 (ca. 1000 mm annual rainfall) exhibit changes in water-use efficiency (WUE), relative to CO_2, at least twice as much as tropical moist forests (c. 4000 mm 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 nitrogen (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 et al., 2019; 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 diameter at breast height (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 favourable moisture conditions return, while others fail to respond (O'Brien et al., 2017). The nature of response also seems to be mediated by neighbourhood 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 in 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 ~3000 m 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 'thermophilisation 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].

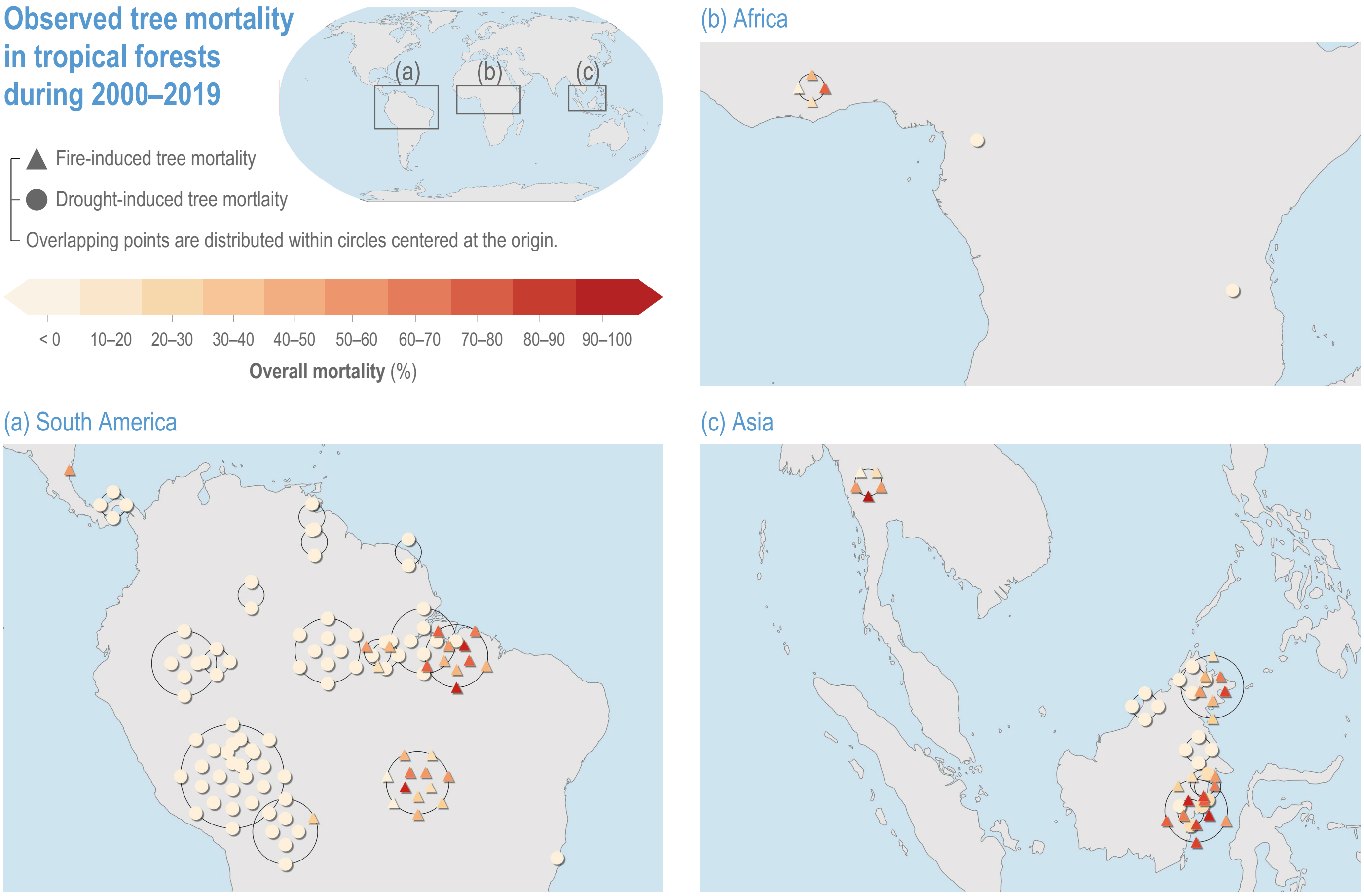

Figure CCP7.4 | Documented instances of tree mortality in tropical moist forests due to fire (1992–2016) and drought (1982–2005). These occurrences were associated with anomalies in precipitation and temperature over the study period. Adapted from Brando et al. (2019).

CCP7.3.3 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 Southeast 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 day^{-1} 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 suggest 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 with <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 with 1990–2010, whereas in an RCP 4.5 scenario, the area burned would be enhanced by 0.9- to 5.4-fold (Le Page et al., 2017).

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