Chapter 10

Climate change and tropical forests

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Introduction

Wright (2010) identified five anthropogenic drivers shaping the future of tropical forests, including land-use change, wood extraction, hunting, atmospheric change, and climate change, with the extent and intensity of these drivers in flux. More than a decade later, the interactions of deforestation and climate change are emerging as the most severe risk to tropical forests in Africa, Asia and the Pacific, and Latin America and the Caribbean. Tropical forests occur throughout the equatorial zone between the Tropic of Cancer (23.5° N) and the Tropic of Capricorn (23.5° S). They occur across a range of dry to wet tropical climates. They encompass high levels of biodiversity and biomass with a high degree of variation in composition, structure, and function due to biogeography, climate, substrate, topography, and disturbance (Muller-Landau et al., 2021). Tropical forests cover less than 10% of the planet's surface and yet house much of the Earth's biodiversity (Giam, 2017), including an estimated 62% of the Earth's terrestrial vertebrate species—more than twice the number found in any other terrestrial biome (Pillay et al., 2022).

Forty-five percent of all forest ecosystems are within the tropics with extensive forests in Central Africa, the Amazon Basin and the Caribbean, and Asia and the Pacific Region (Fig. 10.1). Cazzolla Gatti et al. (2022) report that roughly 43% of all the Earth's tree species occur in South America, primarily in the tropical forests. They range from vast expanses of closed canopy forest to fragmented patches and occur along land-use and management gradients from

FIGURE 10.1 Evergreen broadleaf forest in the Western Ghats in Kerala state, India. In addition to their value for biodiversity conservation, forests in densely populated tropical regions such as India are critical for their provision of many ecosystem services, including climate regulation and provision of abundant clean water supplies needed to sustain downstream agricultural production and meet the needs of growing urban populations. *Photo courtesy J. Parrotta.*

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low to high intensity. Understanding the effects of climate change across this broad gradient of tropical forests is critical to protecting global biodiversity.

The roles of people and climate are intertwined in shaping the future of tropical forests. Tropical forests surround, sustain, and coexist with some of the world's most densely populated and highly developed human populations and some of the most isolated and remote societies. An estimated 1.5 billion people directly depend on or benefit from the goods and services they provide (Lewis, Edwards, & Galbraith, 2015), and much of the rest of the world's population indirectly benefit from their role in climate regulation and other tangible and tangible and intangible benefits. People have interacted with and managed tropical forests for millennia, modifying them for desired species, goods, and services through a wide range of practices and governance regimes and to varying degrees of sustainability (Berkes, Colding, & Folke, 2000; Diamond, 2011; Heckenberger et al., 2003; Nigh, 2008; Parrotta & Trosper, 2012) (Figs. 10.2 and 10.3).

Tropical forests are shaped by and regulate the global climate (Mitchard, 2018). The nature of tropical forests will largely depend on future climates, natural and anthropogenic disturbances, and tropical forest, agricultural, and development policies, practices, and trajectories. The influence of human activity and interventions, including climate action and forest and land management, will be important determinants of tropical forests' future structure and function. Changes in tropical forest systems will affect the Earth's system (Steffen et al., 2018). Future greenhouse gas (GHG) concentrations will depend partly on efforts to reduce emissions, increase sequestration, and mitigate global warming. At the same time, changes in rainfall, temperature, seasonality, and extreme climate disturbances will occur within an already dynamic system affected by deforestation, degradation, land conversion, fire, and other natural and anthropogenic processes. Over the first decade of the 21st century, the pantropical domain experienced the most significant changes in forest area among the tropical, subtropical, temperate, and boreal climate domains, due to natural and anthropogenic processes, with a significant increase in annual forest loss (Hansen et al., 2013). Regionally there is considerable variation in forest cover dynamics, with instances of net forest gain often due to agricultural abandonment. Song et al. (2018) report that between 1982 and 2016, the most significant loss of forest cover was in the dry tropical forest biome (−8%), followed by tropical moist deciduous forest (−2%) in contrast to significant gains in temperate (+33%), boreal (+12%), and subtropical, humid forests (+18%) relative to 1982 forest class area.

The tropical forest biome is well adapted to high temperatures, extreme wet and dry climates, and recurring climate-related disturbances. The biome can persist and continue regulating climate, harboring biodiversity, and providing services under future climate scenarios, but only with increased effectiveness in reversing forest loss through land-use change, increasing sustainable management practices, and better aligning broad governance policies with local benefits and practices. Key trends driven by climate alone are the increasing extent of dry tropical forests and the likelihood of fire, the potential loss of coastal and high-elevation habitats due to shifting life zones, and the loss of unique, restricted habitats harboring rare and endemic elements of biodiversity, such as island forests, cloud forests, or remanent old-growth forests (Fig. 10.4).

FIGURE 10.2 Amazonian forests such as these, near Belém in Pará State, Brazil, provide many environmental services supporting local communities, including enhancement of livelihoods and food security. *Photo courtesy J. Parrotta.*

FIGURE 10.3 On-site processing of sawnwood lumber from waste wood following a timber harvest in a certified forest concession in Ucayali, Peru. Advancing sustainable forest management practices in tropical forests, including reduced wood waste from logging, can contribute to enhanced ecological, economic, and social benefits from managed forests. These practices also may contribute to reduced carbon emissions and increased carbon storage in long-lived wood products from tropical forests, and are increasingly promoted through international agreements on carbon and sustainable development, including the UN Framework Convention on Climate Change Reduced Emissions from Deforestation and Forest Degradation + program. *Photo courtesy K. McGinley.*

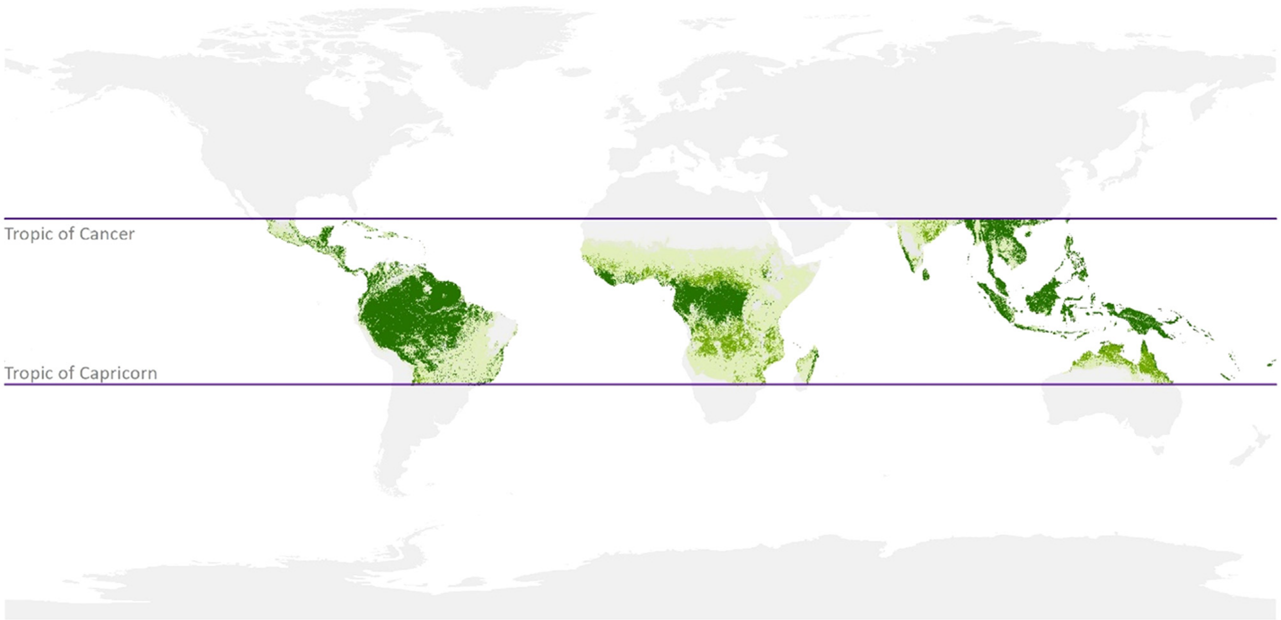

FIGURE 10.4 Three main regions of tropical forests including Latin America and the Caribbean, Africa, Asia, and the Pacific. Colors represent evergreen forests (dark green), deciduous forests (light green), and mixed/unknown forests (yellow-green). *Created using Copernicus forest types raster imagery (Buchhorn et al., 2020) and the terrestrial biomes of the world spatial layers (Olson et al., 2001).*

This chapter describes the projected effects of climate change on tropical forests by region and forest type, the implications for associated ecosystem services and human dimensions, and the interactions with related policy and governance. Awareness of the implications of and vulnerabilities to expected climate change can help prioritize mitigation and adaptation actions to ensure the continued provision of ecosystem services. This chapter also discusses the regional variation in climate projections, implications for climate feedbacks and ecosystem services, a review of representative mitigation and adaptation actions, and a summary of knowledge gaps and research needs.

Climate trends and projections for the tropics

Global climate model simulations and observations indicate smaller long-term warming trends in the tropics than in higher latitudes. However, warming trends will exceed historical variation in the tropics and significantly affect carbon and water cycling (Creed & Van Noordwijk, 2018; Legg, 2021). Temperatures have been rising in all tropical forests and are very likely to continue rising (Pörtner et al., 2022). Significant warming trends between 0.2°C and 0.3°C per decade have been observed in Central America in the last 30 years (Gutiérrez, 2016; Hidalgo, Alfaro, & Quesada-Montano,2017). Warming alone will profoundly affect water cycling but will interact with shifting rainfall patterns and increasing CO_2 concentrations to affect tropical forest composition and structure (Esquivel-Muelbert et al., 2019; McDowell et al., 2018). Observed and projected rainfall patterns in the tropics vary within and among regions. The strong influence of land use and land cover on internal water cycling will have important effects on rainfall and exacerbate the occurrence of drought and fire (Marengo et al., 2018). These changes in the water cycle due to increasing temperatures are expected to affect tropical forests, climate feedbacks, and ecosystem services, likely leading to prolonged drought, longer dry seasons, and increased frequency and intensity of fire in many tropical forests (Legg, 2021). Tropical biodiversity hotspots are likely to experience more extreme heat and droughts further increasing their vulnerability (Barlow et al., 2018; Gould, Castro-Prieto, & Álvarez-Berríos, 2020). Compounding effects on agriculture, food security, water availability, and timber resources will require effective policy and governance responses to protect the range of goods and services that tropical forests provide and the communities that depend on them (Guariguata, Cornelius, Locatelli, Forner, & Sánchez-Azofeifa, 2008; Keenan, 2015; Vira, Wildburger, & Mansourian, 2015).

The question of how climate change may affect the potential dieback of Amazonian tropical forests is of concern not only for the effect on loss of services and impacts on local populations but also as a potential tipping point accelerating global change (Chai et al., 2021; Martin et al., 2021; Wunderling, Donges, Kurths, & Winkelmann, 2021). Observation and recent ecosystem modeling indicate that while rainfall changes have been driving forest compositional changes (Esquivel-Muelbert et al., 2019), Amazonian basin-wide dieback, buffered by landscape variability and tree species genetic diversity inherent in tropical forests, is thought to be unlikely to occur due to projected climate change alone (Chai et al., 2021; Sakschewski et al., 2016). However, interactive effects of climate and land-use change may lead to accelerated forest loss in parts of the Amazon tropical forests (Longo et al., 2020; Martin et al., 2021). Recent analyses indicate forest degradation rates since the early 1990s are higher than previously thought, reaching up to 17% of the Amazon basin (Bullock, Woodcock, Souza, & Olofsson, 2020; Martin et al., 2021; Matricardi et al., 2020; Qin et al., 2021).

Climate change alone will likely drive a significant shift toward drier forests and increasing tree mortality, increasing carbon turnover rates (Brienen et al., 2015; Muller-Landau et al., 2021). Increased tree mortality rates in tropical forests are expected with increased temperatures and vapor pressure deficit (McDowell et al., 2018). Modeling of forest−rainfall feedback by Staal et al. (2020) indicated that under current and future rainfall projections (SSP5-8.5, CMIP6), tropical forests in the Congo Basin, Amazonia, and Australasia vary in their ability to recover forest cover and function following deforestation or other disturbance. According to this study, Congo Basin forests currently have a relatively low capacity for natural regeneration under the current climate, but this will increase under future climate scenarios. Amazonian forests currently have some capacity for regeneration following degradation. However, they may lose such capacity by the end of the century as deforestation interacts with drying and warming trends to reduce water availability. Australasian tropical forests currently have a high capacity for regeneration, which will likely persist under these future scenarios.

Tropical dry and wet forests

One of the most significant determinants of ecological variation in tropical forests is seasonality in rainfall, with moist and wet broadleaved evergreen forests typically experiencing limited seasonal variation in rainfall and tropical dry forests experiencing a prolonged annual dry season (Hasnat & Hossain, 2020; Murphy & Lugo, 1986). Tropical dry forests are highly biodiverse and considered extremely vulnerable to degradation from anthropogenic drivers (Wright, 2010). Relative to tropical moist and wet forests, tropical dry forests have lost more of their historical extent, are underrepresented in protected areas, and are more vulnerable to climate-related disturbances such as extended drought and fire (Hasnat & Hossain, 2020; Janzen, 1988; Miles et al., 2006; Portillo-Quintero et al., 2010). In addition, tropical dry forests have been extensively converted to agriculture and continue to be vulnerable to land conversion (Murphy & Lugo, 1986; Vieira & Scariot, 2006).

Two key approaches to reducing the loss of tropical dry forests and addressing global climate change risks include the large-scale adaptation of current forest and woodland best management practices and the promotion of sustainable agroforestry. Providing extension services and adequate incentives for sustainable management practices such as silvopasturing offer opportunities for small agricultural landholders to retain or increase forest cover, improve water management, and reduce risks of climate change (Sánchez-Romero et al., 2021; Zeppetello et al., 2022). Community-based reforestation efforts supported through governmental and nongovernmental action are being more widely applied but remain underused as a mechanism to capture carbon and increase ecosystem services from tropical dry forests (Lin, Htun, Gritten, & Martin, 2019; Mesa-Sierra, de la Peña-Domene, Campo, & Giardina, 2022; Siyum, 2020).

Tropical wet forests occur within a relatively narrow range of temperatures and water availability and, therefore, may have higher vulnerability to heat and drought conditions exceeding historical ranges (Hilbert, Ostendorf, & Hopkins, 2001; Wright, 2010). Consequently, intact and large contiguous tracts of tropical wet forests may be less vulnerable to climate change than dry forest counterparts in regions with projected increases in rainfall. However, land conversion and fragmentation will increase the susceptibility of intact forests to increased fire, edge effects, and loss of forest ecosystem services (Deb, Phinn, Butt, & McAlpine, 2018). Of particular concern are tropical wet forests of high biodiversity and endemism coupled with limited extent, such as island tropical forests and montane tropical cloud forests (Bruijnzeel, Kappelle, Mulligan, & Scatena, 2010; Gould et al., 2020; Helmer et al., 2019; Karger, Kessler, Lehnert, & Jetz, 2021).

Large-scale reforestation initiatives in response to climate change can be challenging to implement. Community-based and effective management practices, incentives, and regulations to support reforestation, sustainable timber management, and valuation of nontimber forest products and services are proven mechanisms. However, to effectively address climate change, these approaches will require extensive implementation throughout the tropics (Cerullo & Edwards, 2019; Dockendorff et al., 2022; Runting et al., 2019).

Regional variation

Africa

Tropical and subtropical forests in Africa cover approximately 1576 Mha, including 479 Mha of evergreen and deciduous forests and 1097 Mha of mixed forests (Fig. 10.4, Table 10.1), (FAO, 2020). The world's second-largest continent, with a growing population, is highly vulnerable to weather and climate variability (Dosio et al., 2019; Niang et al., 2014). Tropical forest structure and composition vary along west-east and north−south precipitation gradients and variations in soils, substrates, and elevation (Borota, 2012). Generally, aboveground biomass measured in closed canopy tropical forests across several African countries is greater than Amazonian values, with lower stem densities of trees larger than 1 m in diameter. The combination of high aboveground biomass and low stem density are considered a signature structural characteristic of African tropical forests (Lewis et al., 2013). Decadal climate records across central African tropical forests indicate long-term climate trends of rising temperatures, decreasing precipitation, and stronger

TABLE 10.1 Forest area (Mha) within tropical and subtropical moist broadleaf, dry broadleaf, coniferous, savannas/shrublands, flooded grasslands, and savannas, and mangroves biomes in Africa, Latin America, and the Caribbean (LAC), and the Asia and Pacific regions (ASP).

Forest type	Africa (Mha)	LAC (Mha)	ASP (Mha)
Evergreen needle leaf forest	0	2	2
Evergreen broadleaf forest	257	721	392
Deciduous broadleaf forest	222	12	100
Unknown or mixed type	1097	521	279
Total	1576	1256	773

Note: Numbers based on the Copernicus forest types raster imagery (Buchhorn et al., 2020) resampled to a 250 m resolution and the world's terrestrial biomes within the tropical latitudes (Olson et al., 2001).

seasonal moisture deficit (Bennett et al., 2021), with El Niño events typically increasing temperatures and decreasing precipitation. With rising temperatures, mean non-El Niño temperatures in the 2010s exceeded peak temperatures during prior El Niño events, with African forests experiencing record temperatures in 2015−16 (Bennett et al., 2021). Literature of regionally downscaled CORDEX Africa outputs (Coordinated Regional Downscaling Experiment) (Giorgi, Jones, & Asrar, 2009; Jones, Giorgi, & Asrar, 2011) provide projections of mean and extreme climate phenomena (Dosio et al., 2019; Giorgi et al., 2021; Mariotti, Diallo, Coppola, & Giorgi, 2014; Nikulin et al., 2018; Teichmann et al., 2021). Mean annual temperatures have increased 0.2°C−0.5°C per decade since the mid-20th century, and it is very likely that by the end of the century, all regions will see warming in all scenarios. Under RCP8.5 or SSP5-8.5, Central Africa will experience warming larger than 2.5°C, and the rest of Africa will likely experience warming larger than 3°C (Ranasinghe, Ruane, & Vautard, 2021).

Precipitation trends have varied in Africa, with drying in the east, the central and northeastern parts of South Africa, Central Africa, and the Horn of Africa. Climate projections for Africa have many uncertainties, particularly in the hydrologically important Central African region (Mba, Vondou, & Kamsu-Tamo, 2022). There is medium confidence in projected mean precipitation decreases in Southern Africa by the end of the 21st century (Dosio et al., 2019; Teichmann et al., 2021) and indications of wetter wet seasons and drier dry seasons (Gebrechorkos, Hülsmann, & Bernhofer, 2019). The Western Africa region features a gradient in which precipitation decreases in the west and increases in the east (Ranasinghe et al., 2021).

Consequences of significant warming through the end of the century include increased likelihood of both drought and fire and, in those cases with stable or increasing precipitation, potential increases in carbon sequestration. There is evidence of greater resistance in African tropical forests to climate anomalies, including drought events, relative to Amazonian forests (Bennett et al., 2021). Warming temperatures, heat extremes, and more frequent drought and fire are expected to have adverse effects on economic activity and food security across much of Africa and likely produce compounding effects on African tropical forest land-use decisions and governance (Okumu, Kehbila, & Osano, 2021; Pickson & Boateng, 2022). The rapid pace of climate change requires forward-looking conservation measures and governance approaches to protect the provisioning, regulating, supporting, and cultural ecosystem services from African tropical forests (Adeleye, Connor, Annka Herbert, & Simon Graeme Haberle, 2022).

Latin America and the Caribbean

Tropical forests in Latin America (i.e., Mexico, Central America, and South America) and the Caribbean (LAC) cover 1256 Mha and represent 23% of the world's forest areas (FAO, 2020). Approximately 733 Mha are evergreen or deciduous forests, and 521 Mha are mixed or unknown forest types (Fig. 10.4, Table 10.1). The LAC region covers 20 Mkm^2 and hosts an estimated population of 650 million (United Nations Environment Programme, 2016). The region is highly exposed to weather-related hazards, predominantly hurricanes and storms, floods, droughts, and extreme temperatures (Field, Barros, Stocker, & Dahe, 2012), partly moderated by El Nino Southern Oscillation (ENSO) events (Eva et al., 2004). Other main threats to forests relate to land-use changes, notably growing urbanization, habitat degradation, and rapid conversion of natural areas into agricultural lands (Graesser, Aide, Grau, & Ramankutty, 2015; United Nations Environment Programme, 2016).

Latin American and Caribbean forests provide vital ecosystem services for the globe. The region contains about half of the world's remaining broadleaf evergreen tropical forests (Blackman, Epanchin-Niell, Siikamäki, & Velez-Lopez, 2014). They host 50% of the world's terrestrial species, seven of the world's 25 biodiversity hotspots, and 24% of the global protected lands (Alvarez-Malvido et al., 2021; Myers, Mittermeier, Mittermeier, Da Fonseca, & Kent, 2000). These forests contribute significantly to regulating the global climate contributing to the dynamic balance of biogeochemical and hydrological cycles underlying carbon sequestration and storage (Ardila et al., 2020; United Nations Environment Programme, 2016). Tropical forests in LAC sequester large amounts of carbon dioxide from the atmosphere (1.2 + 0.4 Pg C per year) and store 49% of the aboveground carbon in the tropics (Ardila et al., 2020; Saatchi et al., 2011). High deforestation and forest degradation rates threaten the carbon sequestration and storage services these forests provide. Between 2000 and 2017, 24% of the total global forest loss (i.e., 120 Mha) occurred in LAC (Ardila et al., 2020). The conversion of forests to cropland and pasture, mining, and expanding transportation infrastructure are the major causes of deforestation (Alvarez-Berríos & Aide, 2015; Armenteras, González, Retana, & Espelta, 2016; Soares-Filho et al., 2006). While the loss rate of Amazonian forests has slowed between 1975 and 2018, the overall loss rate remains high (Da Cruz, Benayas, Ferreira, Santos, & Schwartz, 2021). Natural regeneration of tropical forests following agricultural abandonment or other recovery to a disturbance in LAC could partially compensate for the loss of primary tropical forests and the carbon sequestration services these provide, contingent upon the long-term persistence of regrowth (Schwartz et al., 2020).

Forest degradation is a critical risk to the tropical forests in LAC. It is estimated that 240 million hectares of these forests have been degraded, primarily due to logging and fire (Armenteras et al., 2016). When considered together, forest loss and degradation in this region contribute to nearly 25% of global GHG emissions (Intergovernmental Panel on Climate Change) (Shukla et al., 2019).

There has been continuous warming across this region since the beginning of the 21st century (Gutiérrez et al., 2021). The average temperature has risen as much as 1° C in most LAC, with warming trends being stronger in lower latitudes and higher elevations. Daily temperature variability has resulted in fewer cold days and more warm days and nights. Variable precipitation patterns have been observed, with areas experiencing higher precipitation, such as in the western Amazon Basin. However, despite regional variability, recent observations show a drying trend over the Amazonian forests caused by global warming, biomass burning, and land-use change. The moisture produced by the forest has decreased, and droughts and wildfire events have increased in parts of the Amazon. Caribbean island forests have seen mixed trends, with little change in lowland and coastal areas and slight increases in rainfall in cloud forests (Jury & Bernard, 2020; Olaya-Arenas, Meléndez-Ackerman, & Pérez, 2020).

Based on higher GHG emissions (SRES A2, RCP8.5), Central and South America may experience end-of-century warming of between 2°C and 6°C. Furthermore, for some parts of the Amazon rainforest, projections based on scenarios of continued high emissions of GHGs indicate an increase of 6°C−7° C by 2100 (Marengo et al., 2018).

Projected rainfall portrays contrasting patterns for the coming decades across South America, with expected increases in some areas and decreases in others. For instance, rainfall reductions are expected in eastern Amazonia (by 5%−20%), while increases are expected in western Amazonia.

Drought, fire, and deregulation outcomes include increased tree mortality in Amazonian forests, affecting biodiversity. Feng, Merow et al. (2021) estimate that since 2000, 2.2%−4.1% of the Amazonian forest has been affected by fire, negatively affecting the extent of the majority of plant and vertebrate species therein. Climate change effects are predicted to cause a 31%−37% decline in Amazonian tree species richness by 2050, and when combined with deforestation trends, the predicted figure increases to 43%−58% (Gomes, Vieira, Salomão, & ter Steege, 2019). Deforestation, global warming, extreme droughts, and increasing wildfire frequency and severity are likely to degrade Amazonian forests, resulting in a gradual replacement of forests by savanna vegetation (Lovejoy & Nobre, 2018; Nobre et al., 2016). The compounding effects of climate change, deforestation, and wildfires could trigger a tipping point for the Amazonian system to shift to nonforest ecosystems at 20%−25% deforestation (Lovejoy & Nobre, 2018). In Central America and the Caribbean, the increase in intensity and frequency of hurricanes may lead to lower aboveground biomass in forests (Lugo, 2000).

Asia and the Pacific

Tropical forests in Asia and the Pacific include moist and dry forests in the Indian subcontinent, Southeast Asia, Australia, and the Pacific Islands. The region's approximately 773 Mha of tropical forests includes 494 Mha of evergreen and deciduous forests and 279 Mha of mixed or unknown forest types within the tropical and subtropical biomes (Fig. 10.4, Table 10.1). Forests in this region include tremendous diversity in the biota as well as people and cultures that extensively use forest resources for hunting, agriculture, timber, and nontimber forest products (Collins, 1991; Feary, Eastburn, Sam, & Kennedy, 2012; Lim, Liang, Camacho, Combalicer, & Singh, 2012; Ramakrishnan et al., 2012).

Deforestation for agricultural and other uses, driven by local and global consumption patterns for agricultural commodities, minerals, and other goods, is the primary impact on biodiversity conservation and ecosystem services these forests provide (Hoang & Kanemoto, 2021). Namkhan, Gale, Savini, and Tantipisanuh (2021) document a 50% loss of mainland Southeast Asian lowland tropical forests and the high vulnerability of remaining forests, including those within protected areas. Feng, Ziegler et al. (2021) indicate total mean annual forest loss for the region was 3.22 Mha yr^{-1} during 2001−19, with 31% occurring in forests of montane mainland Southeast Asia. The frontier of forest loss moved to higher elevations and steeper slopes in the latter decade of that period, leading to unprecedented annual forest carbon loss. In contrast, multiple countries in the region have seen a relatively recent shift from net forest loss to forest recovery (e.g., in Thailand, Vietnam, Laos, Philippines, and Malaysia) attributed in part to economic development leading to agricultural abandonment, forest policy changes, including reforestation campaigns and logging bans, and other factors (De Jong, Liu, Park, & Camacho, 2017; Rudel, Schneider, & Uriarte,2010).

Mean annual surface temperatures show warming trends across Asia during 1960–2015. Accelerated warming has occurred since the 1970s (Legg, 2021), with a higher rate of warming minimum versus maximum temperatures. Thus, the region is experiencing more frequent warm nights (Cheong et al., 2018; Khan, Shahid, Ismail, & Wang, 2019; Zhang & Shen, 2019). Southeast Asian island countries are expected to warm less than mainland areas, with a projected warming of less than 5°C by the end of the century (Almazroui, Saeed, Saeed, Islam, & Ismail, 2020; Basha et al., 2017; Loo, Billa, & Singh, 2015). Southeast Asian tropical forests, particularly in the Indonesian region, are subject to climatic extremes, including droughts during El Niño events and heavy rains in La Niña periods (Agustina, Virgianto, & Fitrianto, 2021). The severity and frequency of climatic extremes are likely to increase and produce significant changes in seasonal rainfall patterns, increase the frequency of flooding and drought, and affect forests directly through increased drought and fire and indirectly through multiple and compounding effects on human–forest interactions and on agricultural, urban, rural, and other social–ecological systems (Osman-Elasha et al., 2009) (Fig. 10.5).

Rainfall varies widely across the region but is characterized by high seasonality, monsoon events, and tropical cyclones (Loo et al., 2015; Malik, Bookhagen, & Mucha, 2016). Rainfall in the region over the last century (1901–2010) has increased at a greater rate in higher versus lower latitudes, with high spatial variability, particularly in Southeast Asia (Knutson & Zeng, 2018). Mean precipitation is likely to increase in most scenarios and over western India (Fig. 10.6) (Gutiérrez et al., 2021). Monsoon circulation will likely increase seasonal contrasts, with wetter wet seasons and drier dry seasons. Zhu et al. (2020) indicate that despite high variability in model projections and significant spatial and seasonal differences in rainfall. There will likely be an increased incidence of flooding and drought across the region, with direct and indirect effects on forests (Deb et al., 2018).

Consequences of warming and increased extremes in seasonality will increase the likelihood of fire, intensify cyclonic events, and affect forest recovery from disturbance. Changes in forest structure and composition will have extensive effects on the communities that depend on forests for their livelihoods and those who value them for the goods and services they provide (Bull et al., 2018; McGinley, Robertson, & Friday, 2019). As climate change alters local and global food and timber markets, conservation priorities, as well as traditional societies and traditional uses of forests are vulnerable (Parrotta & Agnoletti, 2012).

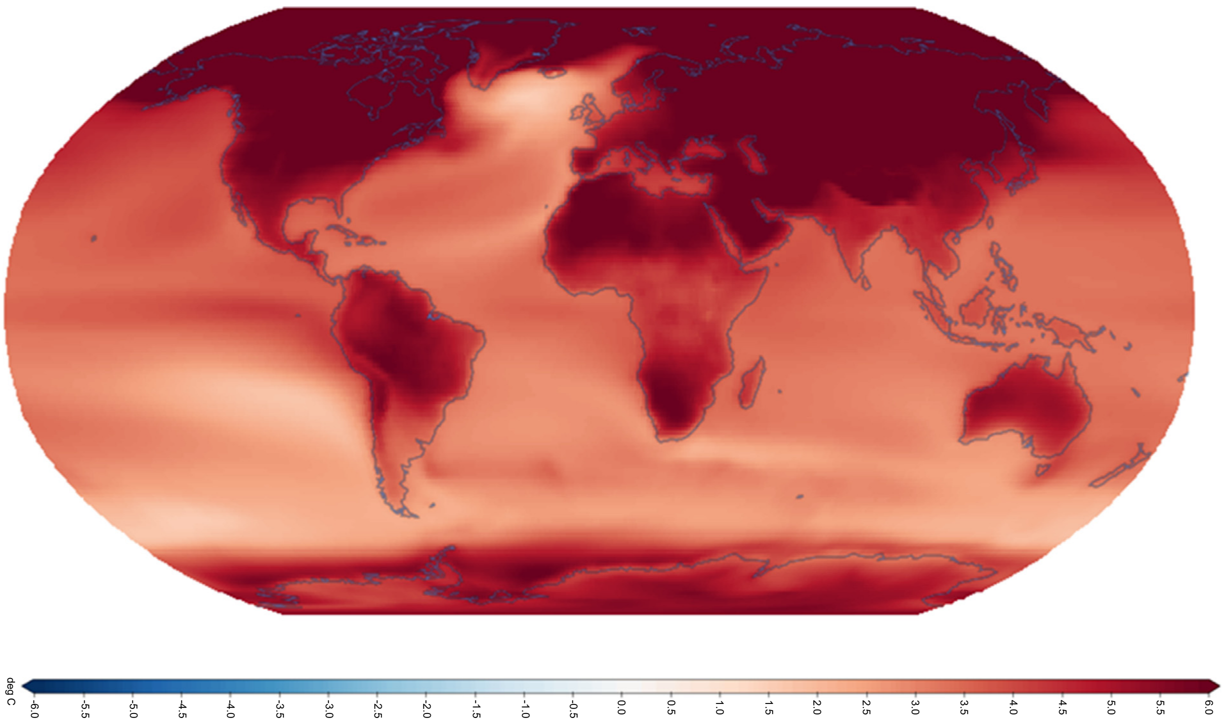

FIGURE 10.5 Temperature projection from IPCC AR6 WG1 indicating the end of the century (relative to 2081–2100) mean annual temperature (T) change (°C) from an ensemble of 34 CMIP6 models using a high emissions scenario (SSP5-8.5). *From Gutiérrez, J. M., Jones R. G., Narisma, G. T., Alves, L. M., Amjad, M., Gorodetskaya, I. V.,... Yoon, J.-H. (2021). Atlas. In Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., et al. (Eds.),* Climate change 2021: The physical science basis. Contribution of Working Group I to the sixth assessment report of the intergovernmental panel on climate change. *Cambridge University Press.*

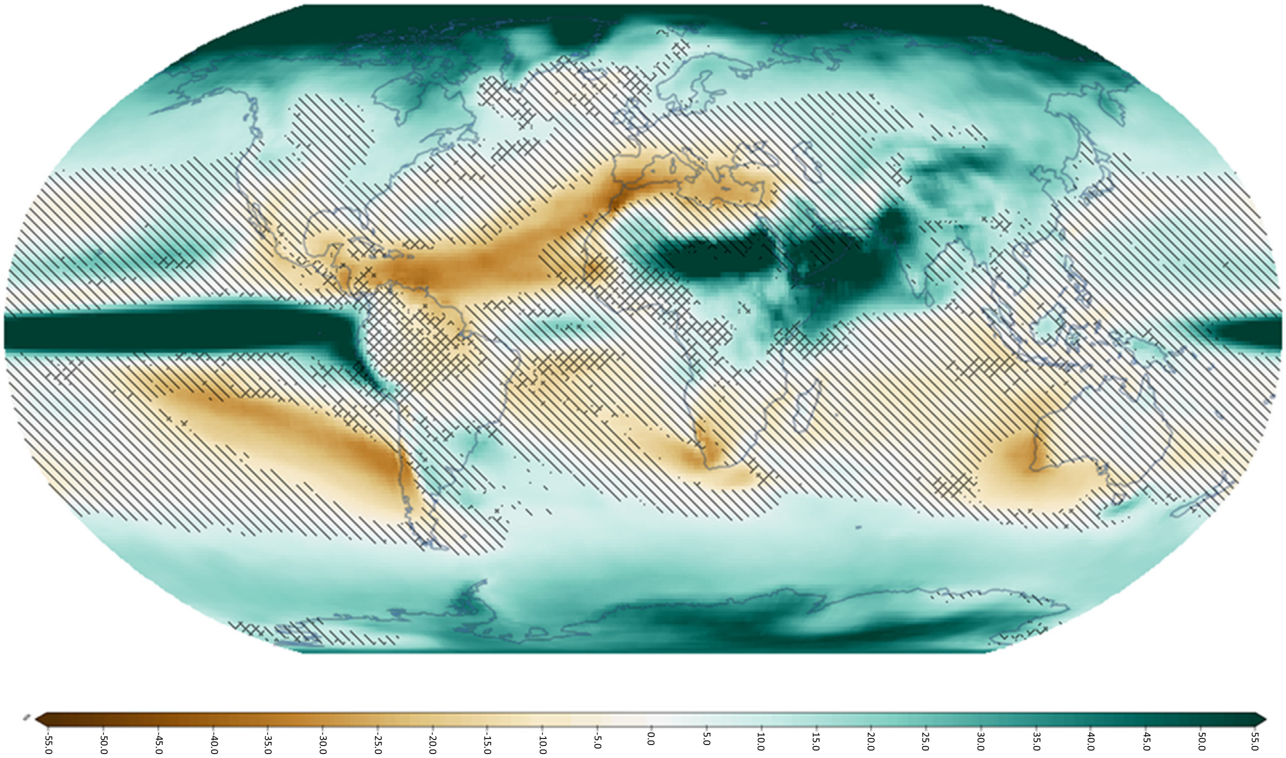

FIGURE 10.6 Percentage change in total precipitation projection from IPCC AR6 WG1 indicating the end of the century (relative to 2081−2100) from an ensemble of 33 CMIP6 models using a high emissions scenario (SSP5-8.5). *From Gutiérrez, J. M., Jones R. G., Narisma, G. T., Alves, L. M., Amjad, M., Gorodetskaya, I. V.,... Yoon, J.-H. (2021). Atlas. In Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., et al. (Eds.),* Climate change 2021: The physical science basis. Contribution of Working Group I to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press.*

Future tropical forests

Increased global atmospheric GHG concentrations drive tropical forest climates above historic temperature ranges. Increased temperatures alone will affect the hydrologic cycle and likely lead to drying, increase the incidence of drought and fire (Van Beusekom et al., 2018), affect moisture-sensitive cloud forest ecosystems (Helmer et al., 2019), and drive the transition of moist to dry tropical forest ecosystems (Bowden et al., 2021; Khalyani et al., 2016). Additionally, shifting rainfall patterns, altered seasonality, increased storm energy, and slower tracking storms all create changing conditions that affect tropical forests' composition, structure, and function across the extent of the tropical biome. Less rain or longer dry seasons will have consequences by reducing productivity and carbon sequestration, increasing the likelihood of fire, reducing food and fiber benefits, altering species composition and distribution, and decreasing biodiversity. Conversely, increased rainfall can increase or maintain productivity, carbon sequestration, and other forest benefits. High rainfall events may adversely affect human activities where there is increased flooding and reduced access to forest resources.

Based solely on potential future climate, the overall extent of forested lands in the tropics could remain stable or increase through natural regeneration, reforestation, and afforestation in all future climate scenarios, providing benefits in carbon sequestration and other ecosystem services, along with climate feedbacks and local cooling effects (Koutika, 2022; Windisch et al., 2022). Nevertheless, human−forest interactions are a significant factor in future tropical forest extent and composition in any climate scenario since human activity, economic development, conservation priorities, and forest and nonforest governance approaches at multiple scales will affect trends in forest use, loss and gain (Davis et al., 2020; Deb et al., 2018; Humphreys et al., 2017; Keenan, 2015; Mackey et al., 2020; McGinley, 2017). Those areas most at risk include tropical forests in all regions where conservation policies are not in place or are not effective, leaving them open to degradation and conversion to other land uses and ultimately to the loss of biologically diverse and culturally and ecologically important forest resources. Additionally, agricultural, mining, and other activities that involve the clearcutting or degradation of tropical forests increase the risk of permanent loss of biodiversity and services

(Edwards et al., 2019; Wimberly et al., 2022). On the other hand, increased forest cover leads to increased rural-to-urban migration or policy interventions that reduce pressures on forests and promote tree planting, such as when agricultural land reverts to forests through natural regeneration, active planting, or both. Therefore, forest policy and management focused on protection, regeneration, and afforestation that integrate future climate conditions in planning will likely be more successful in achieving objectives (Hagerman & Pelai, 2018; Lamb, Erskine, & Parrotta, 2005; McGinley, 2017; Millar, Stephenson, & Stephens, 2007; Seddon et al. 2021).

Actions: mitigation and adaptation to climate change

Tropical forests play a key role in contributing to local and lobal economies, supporting the well-being of millions of people, housing a large share of the planet's biodiversity, and regulating global climate through carbon sequestration and hydrologic cycling. Unfortunately, in recent decades tremendous loss in extent and degradation of ecosystem integrity has occurred in tropical forests around the world. Climate change, bringing higher air temperatures, increasing stream and soil temperatures, more intense storms, and shifting rainfall patterns, will exacerbate vulnerabilities related to illegal logging, deficient or limited management, and ineffective conservation policies. In addition, global pressures on forest lands will increase due to climate change effects on agricultural productivity, urban and rural societies, infrastructure, and human migrations. However, policies, incentives, and best practices at multiple scales can help societies mitigate the increase of GHGs in the atmosphere, adapt to climate changes to support sustained and improved benefits from tropical forests, and improve the lives of people dependent on tropical ecosystem services (Arima, Barreto, Araújo, & Soares-Filho, 2014; Fleischman et al., 2021).

Mitigation of climate change through forest management actions includes the protection and maintenance of mature or old-growth natural forests, reforestation of deforested and degraded areas, improved forest management practices, agroforestry practices that enhance forest cover in agricultural landscapes, and planting trees to increase canopy cover in urban, residential, degraded lands (mining and other causes), managed forests and protected lands. Policy interventions at local, national, and international scales can promote and incentivize mitigation actions. On a global scale, the Paris Climate Agreement (Grassi et al., 2017) acknowledges the role of forests in mitigating climate change by avoiding forest loss, afforestation, reforestation, and improved natural forest management. However, these approaches are not without trade-offs and have significant implications for the state and effectiveness of forest governance, particularly in the tropics (Palomo et al., 2019; Robiou du Pont et al., 2017). At a local scale, mitigation interventions and actions can involve the designation of protected forest areas, state regulation of forest use and access, and tree planting campaigns, which may be promoted through forest protection subsidies, environmental services payments, voluntary forest certification, and forest-based carbon trading. Policies and incentives are most likely to be effective in sustainable forest management by: (1) recognizing fundamental socioeconomic drivers at local, national, and international scales; (2) focusing on key ecosystem services and short- and long-term benefits to local communities; (3) incorporating flexibility to work at small and large scales; (4) ensuring land tenure security; and (5) enabling stable governance structures supported by local and international laws and regulations (Gevaña, Pulhin, & Tapia, 2019; Indrajaya et al., 2022; Robinson, Holland, & Naughton-Treves, 2014).

Climate change policies and approaches involving forests have focused on mitigation rather than adaptation. However, progress in both will be necessary to maintain the multiple benefits of tropical forests at local to global scales (cf., Guariguata et al., 2008). Adaptation actions typically address specific objectives to reduce the socioeconomic effects of climate change and reduce the risks of loss of biodiversity and provisioning services from tropical forests. They can include incentives and approaches for fire and pest prevention and management, reduced impact logging, and assisted migration (Keenan, 2015). Successful adaptation at a global scale will require continued advances in monitoring the extent and condition of forests and the threats and vulnerabilities from climate change, exploitation, and disturbance. Forest resistance and resilience at local scales can be enhanced through effective local community action, application of traditional knowledge, an emphasis on soil health and ecosystem interconnectivity, promoting low-intensity extractive activities, integrating local objectives with long-term policies, and working in an adaptive management framework (Pandit et al., 2020; Parrotta & Agnoletti, 2012; Simonson et al., 2021).

Knowledge gaps and research needs

Knowledge and tools for ensuring the future of tropical forests and the benefits they provide will require advances in social, biophysical, and economic research. Biophysical research to measure and monitor a range of forest attributes with high spatial and temporal resolution in concert with social science to evaluate governance and management practices can provide guidance to reduce GHG emissions and increase carbon sequestration, biodiversity protection, and

FIGURE 10.7 University of Puerto Rico research scientist Dr. Oscar J. Abelleira Martínez inspecting a Pterocarpus officinalis tree introduced by enrichment planting into a novel secondary forest stand dominated by *Spathodea campanulata*. Studies by Dr. Abelleira have been assessing successional pathways of native species planted on seasonally flooded lands previously used for sugar cane in northern Puerto Rico (Abelleira Martínez, 2019; Cruz, 2022; Lugo, Abelleira Martínez, Medina, Aymard, & Heartsill-Scalley, 2020). The tree in the photo was 1 m tall when planted and about 10 m tall at the time the photo was taken, about 10 years after the initial planting. No management interventions were conducted after the initial planting took place. *Photo courtesy Rey Cruz Aguilar.*

sustainable services from tropical forests. Recent advances in remote sensing and monitoring of forest cover and carbon stocks greatly benefit assessing GHG mitigation value gained and lost through carbon sequestration (Fig. 10.7).

The spatial and temporal resolution and the accessibility of this information have increased dramatically (Asner et al., 2010; Aubry-Kientz et al., 2019; Chambers et al., 2007). Further increasing the extent and availability of high-resolution information will make it more equitably accessible to local-scale climate adaptation, mitigation research, and actions. Determining how to integrate these biophysical data more effectively and equitably with socioeconomic data and traditional ecological knowledge at multiple spatial and temporal scales remains challenging for mitigation and adaptation actions.

Understanding the complex design and outcomes of tropical forest governance and its influences on climate mitigation and adaptation actions are required. New knowledge of management benefits and successful implementation methods should be further developed and communicated to employ adaptive management techniques more widely (Bomfim, Pinagé, Emmert, & Kueppers, 2022; Bull et al., 2018; Delabre et al., 2020; Fischer, Giessen, & Günter, 2020). Calls for increasing the flexibility and adaptiveness of tropical forest policy and practice in the context of climate change have long been made (Clark, 2007; Guariguata, 2009; Hahn & Knoke, 2010) and are compelling, but advances on the ground remain limited. Devising approaches that promote and provide space for increased flexibility and responsiveness while also incorporating increased involvement and cooperation of the broad range of tropical forest stakeholders at different scales will be critical to addressing the projected and unforeseen effects of climate change in tropical forests.

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References

Abelleira Martínez, O. J. (2019). Geographic distribution and spatial attributes of African tulip tree forests in north-central Puerto Rico: Implications for social-ecological resilience. *The Journal of Agriculture of the University of Puerto Rico*, *103*, 1−25.

Adeleye, M. A., Connor, S. E., Annka Herbert, A., & Simon Graeme Haberle, S. G. (2022). Toward the saving of global rainforests. *Global Change Biology*, *28*(16), 5006.

Agustina, L., Virgianto, R. H., & Fitrianto, A. N. (2021). *Utilization of remote sensing data for mapping the effect of Indian Ocean Dipole (IOD) and El Nino Southern Oscillation (ENSO) in Sumatra Island*, . *IOP conference series: Earth and environmental science* (893, p. 012062). IOP Publishing.

Almazroui, M., Saeed, S., Saeed, F., Islam, M. N., & Ismail, M. (2020). Projections of precipitation and temperature over the South Asian countries in CMIP6. *Earth Systems and Environment*, *4*(2), 297−320.

Alvarez-Berríos, N. L., & Aide, T. M. (2015). Global demand for gold is another threat for tropical forests. *Environmental Research Letters*, *10*(1), 014006.

Alvarez-Malvido, M., Lázaro, C., De Lamo, X., Juffe-Bignoli, D., Cao, R., Bueno, P., . . .Guerra, F., (Eds.). (2021). *Informe Planeta Protegido 2020: Latinoamérica y El Caribe*. Ciudad de México, México; Cambridge, UK; Gland, Switzerland; Bogotá, Colombia: RedParques, UNEP-WCMC, CMAP-UICN, WWF, CONANP y Proyecto IAPA.

Ardila, J., Arieira, J., Simone Carolina, B., Tathiana, B., Blackman, A., David, O., . . . Nobre, C.A., (2020). *Latin American and Caribbean forests in the 2020s: Trends, challenges, and opportunities*. Retrieved from https://digitalcommons.fiu.edu/cgi/viewcontent.cgi?article = 1207&context = srhreports

Arima, E. Y., Barreto, P., Araújo, E. W., & Soares-Filho, B. (2014). Public policies can reduce tropical deforestation: Lessons and challenges from Brazil. *Land Use Policy*, *41*, 465−473.

Armenteras, D., González, T. M., Retana, J., & Espelta, J. M. (2016). Degradación de bosques en Latinoamérica: Síntesis conceptual, metodologías de evaluación y casos de estudio nacionales. *IBERO-REDD*. Available from https://doi.org/10.13140/RG.2.1.2272.7449.

Asner, G. P., Powell, G. V., Mascaro, J., Knapp, D. E., Clark, J. K., Jacobson, J., . . . Secada, L. (2010). High-resolution forest carbon stocks and emissions in the Amazon. *Proceedings of the National Academy of Sciences*, *107*(38), 16738−16742.

Aubry-Kientz, M., Dutrieux, R., Ferraz, A., Saatchi, S., Hamraz, H., Williams, J., . . . Vincent, G. (2019). A comparative assessment of the performance of individual tree crowns delineation algorithms from ALS data in tropical forests. *Remote Sensing*, *11*(9), 1086.

Barlow, J., França, F., Gardner, T. A., Hicks, C. C., Lennox, G. D., Berenguer, E., . . . Gontijo Leal, C. (2018). The future of hyperdiverse tropical ecosystems. *Nature*, *559*(7715), 517−526. Available from https://doi.org/10.1038/s41586-018-0301-1.

Basha, G., Kishore, P., Ratnam, M. V., Jayaraman, A., Agha Kouchak, A., Ouarda, T. B., & Velicogna, I. (2017). Historical and projected surface temperature over India during the 20th and 21st century. *Scientific Reports*, *7*(1), 1−10.

Bennett, A. C., Dargie, G. C., Cuni-Sanchez, A., Tshibamba Mukendi, J., Hubau, W., Mukinzi, J. M., . . . Adu-Bredu, S. (2021). Resistance of African tropical forests to an extreme climate anomaly. *Proceedings of the National Academy of Sciences*, *118*(21), e2003169118.

Berkes, F., Colding, Johan, & Folke, Carl (2000). Rediscovery of traditional ecological knowledge as adaptive management. *Ecological Applications*, *10*(5), 1251−1262.

Blackman, A., Epanchin-Niell, R., Siikamäki, J., & Velez-Lopez, D. (2014). Biodiversity conservation in Latin America and the Caribbean*:* Prioritizing policies. Routledge. Available from https://doi.org/10.4324/9781315848433.

Bomfim, B., Pinagé, E. R., Emmert, F., & Kueppers, L. M. (2022). Improving sustainable tropical forest management with voluntary carbon markets. *Plant and Soil*, 1−8.

Borota, J. (2012). *Tropical forests: Some African and Asian case studies of composition and structure*. Elsevier.

Bowden, J. H., Terando, A. J., Misra, V., Wootten, A., Bhardwaj, A., Boyles, R., . . . Spero, T. L. (2021). High-resolution dynamically downscaled rainfall and temperature projections for ecological life zones within Puerto Rico and for the US Virgin Islands. *International Journal of Climatology*, *41*(2), 1305−1327.

Brienen, R. J., Phillips, O. L., Feldpausch, T. R., Gloor, E., Baker, T. R., Lloyd, J., . . . Vásquez Martinez, R. (2015). Long-term decline of the Amazon carbon sink. *Nature*, *519*(7543), 344−348.

Bruijnzeel, L. A., Kappelle, M., Mulligan, M., & Scatena, F. N. (2010). Tropical montane cloud forests: State of knowledge and sustainability perspectives in a changing world. In L. A. Bruijnzeel, F. N. Scatena, & L. S. Hamilton (Eds.), *Tropical* montane cloud forests. Science for conservation and management (pp. 691−740). Cambridge, UK: Cambridge University Press.

Buchhorn, M., Smets, B., Bertels, L., De Roo, B., Lesiv, M., Tsendbazar, N.E., . . . Fritz, S. (2020). *Copernicus global land service: Land cover 100m: Collection 3: Epoch 2019: Globe. Version V3. 0.1* [Data set]. Retrieved from https://doi.org/10.5281/ZENODO.3939050.

Bull, G. Q., Boedhihartono, A. K., Bueno, G., Cashore, B., Elliott, C., Langston, J. D., . . . Sayer, J. (2018). Global forest discourses must connect with local forest realities. *International Forestry Review*, *20*(2), 160−166.

Bullock, E. L., Woodcock, C. E., Souza, C., Jr, & Olofsson, P. (2020). Satellite-based estimates reveal widespread forest degradation in the Amazon. *Global Change Biology*, *26*(5), 2956−2969.

Cazzolla Gatti, R., Reich, P. B., Gamarra, J. G., Crowther, T., Hui, C., Morera, A., . . . Serra-Diaz, J. M. (2022). The number of tree species on Earth. *Proceedings of the National Academy of Sciences*, *119*(6), e2115329119.

Cerullo, G. R., & Edwards, D. P. (2019). Actively restoring resilience in selectively logged tropical forests. *Journal of Applied Ecology*, *56*(1), 107−118.

Chai, Y., Martins, G., Nobre, C., von Randow, C., Chen, T., & Dolman, H. (2021). Constraining Amazonian land surface temperature sensitivity to precipitation and the probability of forest dieback. *NPJ Climate and Atmospheric Science*, *4*(1), 1−7.

Chambers, J. Q., Asner, G. P., Morton, D. C., Anderson, L. O., Saatchi, S. S., Espírito-Santo, F. D., . . . Souza, C., Jr (2007). Regional ecosystem structure and function: Ecological insights from remote sensing of tropical forests. *Trends in Ecology & Evolution*, *22*(8), 414−423.

Cheong, W. K., Timbal, B., Golding, N., Sirabaha, S., Kwan, K. F., Cinco, T. A., . . . Han, S. (2018). Observed and modelled temperature and precipitation extremes over Southeast Asia from 1972 to 2010. *International Journal of Climatology*, *38*(7), 3013−3027.

Clark, D. A. (2007). Detecting tropical forests' responses to global climatic and atmospheric change: Current challenges and a way forward. *Biotropica*, *39*(1), 4−19.

Collins, N. M. (1991). *The conservation Atlas of tropical forests: Asia and the Pacifics*. Springer, United Nations, Framework Convention on Climate Change, 2015. Adoption of the Paris agreement.

Creed, I. F., & van Noordwijk, M. (2018). Forest and water on a changing planet: Vulnerability, adaptation and governance opportunities. A global assessment report. *IUFRO World Series*, *38*.

Cruz, R.E. (2022). *Above and below-ground controls on the growth and survival of juvenile trees in enrichment plantings in novel forests of North-Western Puerto Rico* [Thesis]. University of Puerto Rico.

Da Cruz, D. C., Benayas, J. M. R., Ferreira, G. C., Santos, S. R., & Schwartz, G. (2021). An overview of forest loss and restoration in the Brazilian Amazon. *New Forests*, *52*(1), 1−16.

Davis, K. F., Koo, H. I., Dell'Angelo, J., D'Odorico, P., Estes, L., Kehoe, L. J., ... Ribeiro, N. (2020). Tropical forest loss enhanced by large-scale land acquisitions. *Nature Geoscience*, *13*(7), 482−488.

De Jong, W., Liu, J., Park, M. S., & Camacho, L. (2017). Forest transition in Asia: Trends and some theoretical implications. *Forest Policy and Economics*, *100*(76), 1−6.

Deb, J. C., Phinn, S., Butt, N., & McAlpine, C. A. (2018). Climate change impacts on tropical forests: Identifying risks for tropical Asia. *Journal of Tropical Forest Science*, *30*(2), 182−194.

Delabre, I., Boyd, E., Brockhaus, M., Carton, W., Krause, T., Newell, P., ... Zelli, F. (2020). Unearthing the myths of global sustainable forest governance. *Global Sustainability*, *3*.

Diamond, J. (2011). *Collapse: How societies choose to fail or succeed* (Revised ed.). Penguin.

Dockendorff, C., Fuss, S., Agra, R., Guye, V., Herrera, D., & Kraxner, F. (2022). Committed to restoring tropical forests: An overview of Brazil's and Indonesia's restoration targets and policies. *Environmental Research Letters*, *17*(9), 093002.

Dosio, A., Jones, R. G., Jack, C., Lennard, C., Nikulin, G., & Hewitson, B. (2019). What can we know about future precipitation in Africa? Robustness, significance and added value of projections from a large ensemble of regional climate models. *Climate Dynamics*, *53*(9), 5833−5858.

Edwards, D. P., Socolar, J. B., Mills, S. C., Burivalova, Z., Koh, L. P., & Wilcove, D. S. (2019). Conservation of tropical forests in the anthropocene. *Current Biology*, *29*(19), R1008−R1020.

Esquivel-Muelbert, A., Baker, T. R., Dexter, K. G., Lewis, S. L., Brienen, R. J., Feldpausch, T. R., ... Higuchi, N. (2019). Compositional response of Amazon forests to climate change. *Global Change Biology*, *25*(1), 39−56.

Eva, H. D., Belward, A. S., De Miranda, E. E., Di Bella, C. M., Gond, V., Huber, O., ... Fritz, S. (2004). A land cover map of South America. *Global Change Biology*, *10*(5), 731−744. Available from https://doi.org/10.1111/j.1529-8817.2003.00774.x.

FAO. (2020). *Global forest resources assessment 2020: Main report*. Rome: Food and Agriculture Organization of the United Nations.

Feary, S. A., Eastburn, D., Sam, N., & Kennedy, J. (2012). *Western Pacific*. *Traditional forest-related knowledge* (pp. 395−447). Dordrecht: Springer.

Feng, X., Merow, C., Liu, Z., Park, D. S., Roehrdanz, P. R., Maitner, B., ... Pires, M. M. (2021). How deregulation, drought and increasing fire impact Amazonian biodiversity. *Nature*, *597*(7877), 516−521.

Feng, Y., Ziegler, A. D., Elsen, P. R., Liu, Y., He, X., Spracklen, D. V., ... Zeng, Z. (2021). Upward expansion and acceleration of forest clearance in the mountains of Southeast Asia. *Nature Sustainability*, *4*(10), 892−899.

Field, C. B., Barros, V., Stocker, T. F., & Dahe, Q. (Eds.), (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation*. Cambridge University Press, Special report of the intergovernmental panel on climate change.

Fischer, R., Giessen, L., & Günter, S. (2020). Governance effects on deforestation in the tropics: A review of the evidence. *Environmental Science & Policy*, *105*, 84−101.

Fleischman, F., Basant, S., Fischer, H., Gupta, D., Lopez, G. G., Kashwan, P., ... Solorzano, C. R. (2021). How politics shapes the outcomes of forest carbon finance. *Current Opinion in Environmental Sustainability*, *51*, 7−14.

Gebrechorkos, S. H., Hülsmann, S., & Bernhofer, C. (2019). Regional climate projections for impact assessment studies in East Africa. *Environmental Research Letters*, *14*(4), 044031.

Gevaña, D. T., Pulhin, J. M., & Tapia, M. A. (2019). *Fostering climate change mitigation through a community-based approach: Carbon stock potential of community-managed mangroves in the Philippines*. *Coastal management* (pp. 271−282). Academic Press.

Giam, X. (2017). Global biodiversity loss from tropical deforestation. *Proceedings of the National Academy of Sciences*, *114*(23), 5775−5777.

Giorgi, F., Coppola, E., Jacob, D., Teichmann, C., Abba Omar, S., Ashfaq, M., ... Cavazos, T. (2021). The CORDEX-CORE EXP-I initiative: Description and highlight results from the initial analysis. *Bulletin of the American Meteorological Society*, 1−52.

Giorgi, F., Jones, C., & Asrar, G. R. (2009). Addressing climate information needs at the regional level: The CORDEX framework. *World Meteorological Organization (WMO) Bulletin*, *58*(3), 175.

Gomes, V. H., Vieira, I. C., Salomão, R. P., & ter Steege, H. (2019). Amazonian tree species threatened by deforestation and climate change. *Nature Climate Change*, *9*(7), 547−553.

Gould, W. A., Castro-Prieto, J., & Álvarez-Berríos, N. L. (2020). Climate change and biodiversity conservation in the Caribbean islands. *Encyclopedia of the World's Biomes*, 114−125.

Graesser, J., Aide, T. M., Grau, H. R., & Ramankutty, N. (2015). Cropland/pastureland dynamics and the slowdown of deforestation in Latin America. *Environmental Research Letters*, *10*(3), 034017. Available from https://doi.org/10.1088/1748-9326/10/3/034017.

Grassi, G., House, J., Dentener, F., Federici, S., den Elzen, M., & Penman, J. (2017). The key role of forests in meeting climate targets requires science for credible mitigation. *Nature Climate Change*, *7*(3), 220−226.

Guariguata, M. R. (2009). Tropical forest management and climate change adaptation. *Revista de Estudios Sociales*, *32*, 98−112.
Guariguata, M. R., Cornelius, J. P., Locatelli, B., Forner, C., & Sánchez-Azofeifa, G. A. (2008). Mitigation needs adaptation: Tropical forestry and climate change. *Mitigation and Adaptation Strategies for Global Change*, *13*(8), 793−808.
Gutiérrez, E.O. P. (2016). Impactos Del Cambio Climático y Medidas de Adaptación En Cuba. *Anales de La Academia de Ciencias de Cuba*, *5*(3).
Gutiérrez, J. M., Jones, R. G., Narisma, G. T., Alves, L. M., Amjad, M., Gorodetskaya, I. V., … … Yoon, J.-H. (2021). Atlas. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, et al. (Eds.), *Climate change 2021: The physical science basis. Contribution of Working Group I to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press.
Hagerman, S. M., & Pelai, R. (2018). Responding to climate change in forest management: Two decades of recommendations. *Frontiers in Ecology and the Environment*, *16*(10), 579−587.
Hahn, W. A., & Knoke, T. (2010). Sustainable development and sustainable forestry: analogies, differences, and the role of flexibility. *European Journal of Forest Research*, *129*(5), 787−801. Available from https://doi.org/10.1007/s10342-010-0385-0.
Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., … Kommareddy, A. (2013). High-resolution global maps of 21st-century forest cover change. *Science (New York, N.Y.)*, *342*(6160), 850−853. Available from https://doi.org/10.1126/science.1244693.
Hasnat, G. T., & Hossain, M. K. (2020). *Global overview of tropical dry forests*. *Handbook of research on the conservation and restoration of tropical dry forests* (pp. 1−23). Hershey, PA: IGI Global.
Heckenberger, M. J., Kuikuro, A., Kuikuro, U. T., Russell, J. C., Schmidt, M., Fausto, C., & Franchetto, B. (2003). Amazonia 1492: Pristine forest or cultural parkland? *Science (New York, N.Y.)*, *301*(5640), 1710−1714.
Helmer, E. H., Gerson, E. A., Baggett, L. S., Bird, B. J., Ruzycki, T. S., & Voggesser, S. M. (2019). Neotropical cloud forests and páramo to contract and dry from declines in cloud immersion and frost. *PLoS One*, *14*(4), e0213155. Available from https://doi.org/10.1371/journal.pone.0213155.
Hidalgo, H. G., Alfaro, E. J., & Quesada-Montano, B. (2017). Observed (1970−1999) climate variability in Central America using a high-resolution meteorological dataset with implication to climate change studies. *Climatic Change*, *141*(1), 13−28. Available from https://doi.org/10.1007/s10584-016-1786-y.
Hilbert, D. W., Ostendorf, B., & Hopkins, M. S. (2001). Sensitivity of tropical forests to climate change in the humid tropics of north Queensland. *Austral Ecology*, *26*(6), 590−603.
Hoang, N. T., & Kanemoto, K. (2021). Mapping the deforestation footprint of nations reveals growing threat to tropical forests. *Nature Ecology & Evolution*, *5*(6), 845−853. Available from https://doi.org/10.1038/s41559-021-01417-z.
Humphreys, D., Cashore, B., Visseren-Hamakers, I. J., De Jong, W., McGinley, K., Denvir, A., … Lupberger, S. (2017). Towards durable multistakeholder-generated solutions: The pilot application of a problem-oriented policy learning protocol to legality verification and community rights in Peru. *International Forestry Review*, *19*(3), 278−293.
Indrajaya, Y., Yuwati, T. W., Lestari, S., Winarno, B., Narendra, B. H., Nugroho, H. Y. S. H., … Putra, P. B. (2022). Tropical forest landscape restoration in Indonesia: A review. *Land*, *11*(3), 328. Available from https://doi.org/10.3390/land11030328.
Janzen, D. H. (1988). Tropical dry forests. *Biodiversity*, *15*, 130−137.
Jones, C., Giorgi, F., & Asrar, G., (2011). The coordinated regional downscaling experiment (CORDEX). An international downscaling link to CMIP5. In CLIVAR Exchanges (Vol. 56, No. 16, pp. 34−40). International CLIVAR Project Office, Southampton, United Kingdom.
Jury, M. R., & Bernard, D. (2020). Climate trends in the East Antilles islands. *International Journal of Climatology*, *40*(1), 36−51.
Karger, D. N., Kessler, M., Lehnert, M., & Jetz, W. (2021). Limited protection and ongoing loss of tropical cloud forest biodiversity and ecosystems worldwide. *Nature Ecology & Evolution*, *5*(6), 854−862.
Keenan, R. J. (2015). Climate change impacts and adaptation in forest management: A review. *Annals of Forest Science*, *72*(2), 145−167.
Khalyani, A. H., Gould, W. A., Harmsen, E., Terando, A., Quinones, M., & Collazo, J. A. (2016). Climate change implications for tropical islands: Interpolating and interpreting statistically downscaled GCM projections for management and planning. *Journal of Applied Meteorology and Climatology*, *55*(2), 265−282. Available from https://doi.org/10.1175/JAMC-D-15-0182.1.
Khan, N., Shahid, S., Ismail, T. B., & Wang, X. J. (2019). Spatial distribution of unidirectional trends in temperature and temperature extremes in Pakistan. *Theoretical and Applied Climatology*, *136*(3), 899−913. Available from https://doi.org/10.1007/s00704-018-2520-7.
Knutson, T. R., & Zeng, F. (2018). Model assessment of observed precipitation trends over land regions: Detectable human influences and possible low bias in model trends. *Journal of Climate*, *31*(12), 4617−4637. Available from https://doi.org/10.1175/JCLI-D-17-0672.1.
Koutika, L. S. (2022). Boosting C sequestration and land restoration through forest management in tropical ecosystems: A mini-review. *Ecologies*, *3* (1), 13−29. Available from https://doi.org/10.3390/ecologies3010003.
Lamb, D., Erskine, P. D., & Parrotta, J. A. (2005). Restoration of degraded tropical forest landscapes. *Science (New York, N.Y.)*, *310*(5754), 1628−1632. Available from https://doi.org/10.1126/science.1111773.
Legg, S. (2021). IPCC, 2021: Climate change 2021-The physical science basis. *Interaction*, *49*(4), 44−45.
Lewis, S. L., Edwards, D. P., & Galbraith, D. (2015). Increasing human dominance of tropical forests. *Science (New York, N.Y.)*, *349*(6250), 827−832.
Lewis, S. L., Sonké, B., Sunderland, T., Begne, S. K., Lopez-Gonzalez, G., Van Der Heijden, G. M., … Bastin, J. F. (2013). Aboveground biomass and structure of 260 African tropical forests. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *368*(1625), 20120295. Available from https://doi.org/10.1098/rstb.2012.0295.
Lim, H. F., Liang, L., Camacho, L. D., Combalicer, E. A., & Singh, S. K. K. (2012). Southeast Asia. In John A. Parrotta, & Ronald L. Trosper (Eds.), *Traditional forest-related knowledge* (pp. 357−394). Dordrecht: Springer.
Lin, T., Htun, K. T., Gritten, D., & Martin, A. R. (2019). The contribution of community forestry to climate change adaptive capacity in tropical dry forests: lessons from Myanmar. *International Forestry Review*, *21*(3), 324−340.

Longo, M., Saatchi, S., Keller, M., Bowman, K., Ferraz, A., Moorcroft, P. R., ... Derroire, G. (2020). Impacts of degradation on water, energy, and carbon cycling of the Amazon tropical forests. *Journal of Geophysical Research: Biogeosciences*, *125*(8). Available from https://doi.org/10.1029/2020JG005677, e2020JG005677.

Loo, Y. Y., Billa, L., & Singh, A. (2015). Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. *Geoscience Frontiers*, *6*(6), 817−823. Available from https://doi.org/10.1016/j.gsf.2014.02.009.

Lovejoy, T. E., & Nobre, C. (2018). Amazon tipping point. *Science Advances*, *4*(2), eaat2340. Available from https://doi.org/10.1126/sciadv.aat2340.

Lugo, A. E. (2000). Effects and outcomes of Caribbean Hurricanes in a climate change scenario. *Science of the Total Environment*, *262*(3), 243−251. Available from https://doi.org/10.1016/S0048-9697(00)00526-X.

Lugo, A. E., Abelleira Martínez, O. J., Medina, E., Aymard, G., & Heartsill-Scalley, T. (2020). Novelty in the tropical forests of the 21st century. *Advances in Ecological Research*, *62*, 53−116.

Mackey, B., Kormos, C. F., Keith, H., Moomaw, W. R., Houghton, R. A., Mittermeier, R. A., ... Hugh, S. (2020). Understanding the importance of primary tropical forest protection as a mitigation strategy. *Mitigation and Adaptation Strategies for Global Change*, *25*(5), 763−787. Available from https://doi.org/10.1007/s11027-019-09891-4.

Malik, N., Bookhagen, B., & Mucha, P. J. (2016). Spatiotemporal patterns and trends of Indian monsoonal rainfall extremes. *Geophysical Research Letters*, *43*(4), 1710−1717. Available from https://doi.org/10.1002/2016GL067841.

Marengo, J. A., Souza, C. M., Jr, Thonicke, K., Burton, C., Halladay, K., Betts, R. A., ... Soares, W. R. (2018). Changes in climate and land use over the Amazon region: Current and future variability and trends. *Frontiers in Earth Science*, *6*, 228. Available from https://doi.org/10.3389/feart.2018.00228.

Mariotti, L., Diallo, I., Coppola, E., & Giorgi, F. (2014). Seasonal and intraseasonal changes of African monsoon climates in 21st century CORDEX projections. *Climatic Change*, *125*(1), 53−65. Available from https://doi.org/10.1007/s10584-014-1097-0.

Martin, M. A., Sendra, O. A., Bastos, A., Bauer, N., Bertram, C., Blenckner, T., ... Bustamante, M. (2021). Ten new insights in climate science 2021: A horizon scan. *Global Sustainability*, *4*. Available from https://doi.org/10.1017/sus.2021.25.

Matricardi, E. A. T., Skole, D. L., Costa, O. B., Pedlowski, M. A., Samek, J. H., & Miguel, E. P. (2020). Long-term forest degradation surpasses deforestation in the Brazilian Amazon. *Science (New York, N.Y.)*, *369*(6509), 1378−1382. Available from https://doi.org/10.1126/science.abb3021.

Mba, W. P., Vondou, D. A., & Kamsu-Tamo, P. H. (2022). Central African climate: Advances and gaps. *Congo Basin Hydrology, Climate, and Biogeochemistry: A Foundation for the Future*, 13−23. Available from https://doi.org/10.1002/9781119657002.ch2.

McDowell, N., Allen, C. D., Anderson-Teixeira, K., Brando, P., Brienen, R., Chambers, J., ... Espirito-Santo, F. (2018). Drivers and mechanisms of tree mortality in moist tropical forests. *New Phytologist*, *219*(3), 851−869. Available from https://doi.org/10.1111/nph.15027.

McGinley, K. A. (2017). Adapting tropical forest policy and practice in the context of the Anthropocene: Opportunities and challenges for the El Yunque National Forest in Puerto Rico. *Forests*, *8*(7), 259.

McGinley, K. A., Robertson, G. C., & Friday, K. S. (2019). Examining the sustainability of tropical island forests: Advances and challenges in measurement, monitoring, and reporting in the US Caribbean and Pacific. *Forests*, *10*(11), 946. Available from https://doi.org/10.3390/f10110946.

Mesa-Sierra, N., de la Peña-Domene, M., Campo, J., & Giardina, C. P. (2022). Restoring mexican tropical dry forests: A national review. *Sustainability*, *14*(7), 3937.

Miles, L., Newton, A. C., DeFries, R. S., Ravilious, C., May, I., Blyth, S., ... Gordon, J. E. (2006). A global overview of the conservation status of tropical dry forests. *Journal of Biogeography*, *33*(3), 491−505.

Millar, C. I., Stephenson, N. L., & Stephens, S. L. (2007). Climate change and forests of the future: managing in the face of uncertainty. *Ecological Applications*, *17*(8), 2145−2151.

Mitchard, E. T. (2018). The tropical forest carbon cycle and climate change. *Nature*, *559*(7715), 527−534. Available from https://doi.org/10.1038/s41586-018-0300-2.

Muller-Landau, H. C., Cushman, K. C., Arroyo, E. E., Martinez Cano, I., Anderson-Teixeira, K. J., & Backiel, B. (2021). Patterns and mechanisms of spatial variation in tropical forest productivity, woody residence time, and biomass. *New Phytologist*, *229*(6), 3065−3087.

Murphy, P. G., & Lugo, A. E. (1986). Ecology of tropical dry forest. *Annual Review of Ecology and Systematics*, 67−88.

Myers, N., Mittermeier, R. A., Mittermeier, C. G., Da Fonseca, G. A., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), 853−858. Available from https://doi.org/10.1038/35002501.

Namkhan, M., Gale, G. A., Savini, T., & Tantipisanuh, N. (2021). Loss and vulnerability of lowland forests in mainland Southeast Asia. *Conservation Biology*, *35*(1), 206−215. Available from https://doi.org/10.1111/cobi.13538.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J., & Urquhart, P. (2014). Africa. In *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of working Group II to the fifth assessment* (pp. 1199−1266). Cambridge University Press. Report of the intergovernmental panel on climate change.

Nigh, R. (2008). Trees, fire and farmers: Making woods and soil in the Maya forest. *Journal of Ethnobiology*, *28*(2), 231−243.

Nikulin, G., Lennard, C., Dosio, A., Kjellström, E., Chen, Y., Hänsler, A., ... van Meijgaard, E. (2018). The effects of 1.5 and 2 degrees of global warming on Africa in the CORDEX ensemble. *Environmental Research Letters*, *13*(6), 065003. Available from https://doi.org/10.1088/1748-9326/aab1b1.

Nobre, C. A., Sampaio, G., Borma, L. S., Castilla-Rubio, J. C., Silva, J. S., & Cardoso, M. (2016). Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *Proceedings of the National Academy of Sciences*, *113*(39), 10759−10768. Available from https://doi.org/10.1073/pnas.1605516113.

Okumu, B., Kehbila, A. G., & Osano, P. (2021). A review of water-forest-energy-food security nexus data and assessment of studies in East Africa. *Current Research in Environmental Sustainability*, *3*, 100045. Available from https://doi.org/10.1016/j.crsust.2021.100045.

Olaya-Arenas, P., Meléndez-Ackerman, E. J., & Pérez, M. E. (2020). Long-term temperature and precipitation trends in the Luquillo Mountains, and their relationships to global atmospheric indices used in climate change predictions. *Caribbean Journal of Science*, *50*(1), 107−131.

Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V., Underwood, E. C., ... Loucks, C. J. (2001). Terrestrial ecoregions of the world: A new map of life on earth A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *Bioscience*, *51*(11), 933−938, https://doi.org/10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2.

Osman-Elasha, B., Adger, N., Brockhaus, M., Colfer, C. J. P., Sohngen, B., Dafalla, T., ... Robledo, C. (2009). Future socio-economic impacts and vulnerabilities. In R. Seppala, A. Buck, & P. Katila (Eds.), *Adaptation of forests and people to climate change. A global assessment report.* IUFRO world series (22, pp. 101−122). Helsinki, Finland: IUFRO.

Palomo, I., Dujardin, Y., Midler, E., Robin, M., Sanz, M. J., & Pascual, U. (2019). Modeling trade-offs across carbon sequestration, biodiversity conservation, and equity in the distribution of global REDD + funds. *Proceedings of the National Academy of Sciences*, *116*(45), 22645−22650.

Pandit, R., Parrotta, J. A., Chaudhary, A. K., Karlen, D. L., Mascia Vieira, D. L., Anker, Y., ... Ntshotsho, P. (2020). A framework to evaluate land degradation and restoration responses for improved planning and decision-making. *Ecosystems and People*, *16*(1), 1−18. Available from https://doi.org/10.1080/26395916.2019.1697756.

Parrotta, J. A., & Agnoletti, M. (2012). Traditional forest-related knowledge and climate change. In (edited byJohn A. Parrotta, & Ronald L. Trosper (Eds.), *Traditional forest-related knowledge* (12Dordrecht: Springer, World Forests. Available from https://doi.org/10.1007/978-94-007-2144-9_13.

Parrotta, J. A., & Trosper, R. L. (Eds.), (2012). *Traditional forest-related knowledge: Sustaining communities, ecosystems and biocultural diversity*. Dordrecht: Springer.

Pickson, R. B., & Boateng, E. (2022). Climate change: A friend or foe to food security in Africa. *Environment, Development and Sustainability*, *24* (3), 4387−4412. Available from https://doi.org/10.1007/s10668-021-01621-8.

Pillay, R., Venter, M., Aragon-Osejo, J., González-del-Pliego, P., Hansen, A. J., Watson, J. E., & Venter, O. (2022). Tropical forests are home to over half of the world's vertebrate species. *Frontiers in Ecology and the Environment*, *20*(1), 10−15.

Portillo-Quintero, C. A., & Sánchez-Azofeifa, G. A. (2010). Extent and conservation of tropical dry forests in the Americas. *Biological Conservation*, *143*(1), 144−155.

Pörtner, H.O., Roberts, D.C., Adams, H., Adler, C., Aldunce, P., Ali, E., ... Birkmann, J. (2022). Climate change 2022: Impacts, adaptation and vulnerability. IPCC sixth assessment report. IPCC. Available from https://edepot.wur.nl/565644

Qin, Y., Xiao, X., Wigneron, J. P., Ciais, P., Brandt, M., Fan, L., ... Zhang, Y. (2021). Carbon loss from forest degradation exceeds that from deforestation in the Brazilian Amazon. *Nature Climate Change*, *11*(5), 442−448. Available from https://doi.org/10.1038/s41558-021-01026-5.

Ramakrishnan, P. S., Rao, K. S., Chandrashekara, U. M., Chhetri, N., Gupta, H. K., Patnaik, S., ... Sharma, E. (2012). South Asia. In John A. Parrotta, & Ronald L. Trosper (Eds.), *Traditional forest-related knowledge* (edited by, pp. 315−356). Dordrecht: Springer.

Ranasinghe, R., Ruane, A. C., & Vautard, R. (2021). *Climate change information for regional impact and for risk assessment*, . *Climate change 2021: The physical science basis. Contribution of Working Group I to the sixth assessment report of the intergovernmental panel on climate change* (5, pp. 4215−4232). Cambridge University Press.

Robinson, B. E., Holland, M. B., & Naughton-Treves, L. (2014). Does secure land tenure save forests? A meta-analysis of the relationship between land tenure and tropical deforestation. *Global Environmental Change*, *29*, 281−293.

Robiou du Pont, Y., Jeffery, M. L., Gütschow, J., Rogelj, J., Christoff, P., & Meinshausen, M. (2017). Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change*, *7*(1), 38−43.

Rudel, T. K., Schneider, L., & Uriarte, M. (2010). Forest transitions: An introduction. *Land Use Policy*, *27*(2), 95−97.

Runting, R. K., Griscom, B. W., Struebig, M. J., Satar, M., Meijaard, E., Burivalova, Z., ... Wells, J. A. (2019). Larger gains from improved management over sparing−sharing for tropical forests. *Nature Sustainability*, *2*(1), 53−61.

Saatchi, S. S., Harris, N. L., Brown, S., Lefsky, M., Mitchard, E. T., Salas, W., ... Petrova, S. (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences*, *108*(24), 9899−9904.

Sakschewski, B., Von Bloh, W., Boit, A., Poorter, L., Peña-Claros, M., Heinke, J., ... Thonicke, K. (2016). Resilience of Amazon forests emerges from plant trait diversity. *Nature Climate Change*, *6*(11), 1032−1036. Available from https://doi.org/10.1038/nclimate3109.

Sánchez-Romero, R., Balvanera, P., Castillo, A., Mora, F., García-Barrios, L. E., & González-Esquivel, C. E. (2021). Management strategies, silvopastoral practices and socioecological drivers in traditional livestock systems in tropical dry forests: An integrated analysis. *Forest Ecology and Management*, *479*, 118506.

Schwartz, N. B., Feng, X., Muscarella, R., Swenson, N. G., Umaña, M. N., Zimmerman, J. K., & Uriarte, M. (2020). Topography and traits modulate tree performance and drought response in a tropical forest. *Frontiers in Forests and Global Change*, *3*, 596256. Available from https://doi.org/10.3389/ffgc.2020.596256.

Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., ... Turner, B. (2021). Getting the message right on nature-based solutions to climate change. *Global Change Biology*, *27*(8), 1518−1546. Available from https://doi.org/10.1111/gcb.15513.

Shukla, P.R., Skeg, J., Buendia, E.C., Masson-Delmotte, V., Pörtner, H.O., Roberts, D.C., ... Ferrat, M. (2019). *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. IPCC.

Simonson, W. D., Miller, E., Jones, A., García-Rangel, S., Thornton, H., & McOwen, C. (2021). Enhancing climate change resilience of ecological restoration—A framework for action. *Perspectives in Ecology and Conservation*, *19*(3), 300−310. Available from https://doi.org/10.1016/j.pecon.2021.05.002.

Siyum, Z. G. (2020). Tropical dry forest dynamics in the context of climate change: Syntheses of drivers, gaps, and management perspectives. *Ecological Processes*, *9*(1), 1−16.

Soares-Filho, B. S., Nepstad, D. C., Curran, L. M., Cerqueira, G. C., Garcia, R. A., Ramos, C. A., ... Schlesinger, P. (2006). Modelling conservation in the Amazon basin. *Nature*, *440*(7083), 520−523. Available from https://doi.org/10.1038/nature04389.

Song, X. P., Hansen, M. C., Stehman, S. V., Potapov, P. V., Tyukavina, A., Vermote, E. F., & Townshend, J. R. (2018). Global land change from 1982 to 2016. *Nature*, *560*(7720), 639−643.

Staal, A., Fetzer, I., Wang-Erlandsson, L., Bosmans, J. H., Dekker, S. C., van Nes, E. H., ... Tuinenburg, O. A. (2020). Hysteresis of tropical forests in the 21st century. *Nature Communications*, *11*(1), 1−8.

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., ... Donges, J. F. (2018). Trajectories of the Earth system in the Anthropocene. *Proceedings of the National Academy of Sciences*, *115*(33), 8252−8259.

Teichmann, C., Jacob, D., Remedio, A. R., Remke, T., Buntemeyer, L., Hoffmann, P., ... Sieck, K. (2021). Assessing mean climate change signals in the global CORDEX-CORE ensemble. *Climate Dynamics*, *57*(5), 1269−1292. Available from https://doi.org/10.1007/s00382-020-05494-x.

United Nations Environment Programme. (2016). *GEO-6 Regional Assessment for Latin America and the Caribbean*.

Van Beusekom, A. E., Gould, W. A., Monmany, A. C., Henareh Khalyani, A., Quiñones, M., Fain, S. J., ... González, G. (2018). Fire weather and likelihood: Characterizing climate space for fire occurrence and extent in Puerto Rico. *Climatic Change*, *146*(1−2), 117−131. Available from https://doi.org/10.1007/s10584-017-2045-6.

Vieira, D. L., & Scariot, A. (2006). Principles of natural regeneration of tropical dry forests for restoration. *Restoration Ecology*, *14*(1), 11−20.

Vira, B., Wildburger, C., & Mansourian, S. (2015). *Forests and food: Addressing hunger and nutrition across sustainable landscapes* (Hardback). https://doi.org/10.11647/OBP.0085

Wimberly, M. C., Dwomoh, F. K., Numata, I., Mensah, F., Amoako, J., Nekorchuk, D. M., & McMahon, A. (2022). Historical trends of degradation, loss, and recovery in the tropical forest reserves of Ghana. *International Journal of Digital Earth*, *15*(1), 30−51. Available from https://doi.org/10.1080/17538947.2021.2012533.

Windisch, M. G., Humpenöder, F., Lejeune, Q., Schleussner, C. F., Lotze-Campen, H., & Popp, A. (2022). Accounting for local temperature effect substantially alters afforestation patterns. *Environmental Research Letters*, *17*(2), 024030. Available from https://doi.org/10.1088/1748-9326/ac4f0e.

Wright, S. J. (2010). The future of tropical forests. *Annals of the New York Academy of Sciences*, *1195*(1), 1−27.

Wunderling, N., Donges, J. F., Kurths, J., & Winkelmann, R. (2021). Interacting tipping elements increase risk of climate domino effects under global warming. *Earth System Dynamics*, *12*(2), 601−619. Available from https://doi.org/10.5194/esd-12-601-2021.

Zeppetello, L. R. V., Cook-Patton, S. C., Parsons, L. A., Wolff, N. H., Kroeger, T., Battisti, D. S., ... Masuda, Y. J. (2022). Consistent cooling benefits of silvopasture in the tropics. *Nature Communications*, *13*(1), 1−9.

Zhang, J., & Shen, Y. (2019). Spatio-temporal variations in extreme drought in China during 1961−2015. *Journal of Geographical Sciences*, *29*(1), 67−83.

Zhu, H., Jiang, Z., Li, J., Li, W., Sun, C., & Li, L. (2020). Does CMIP6 inspire more confidence in simulating climate extremes over China? *Advances in Atmospheric Sciences*, *37*(10), 1119−1132.