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Recent advances and challenges in monitoring and modeling of disturbances in tropical moist forests

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Tropical moist forests have been severely affected by natural and anthropogenic disturbances, leading to substantial changes in global carbon cycle and climate. These effects have received great attention in scientific research and debates. Here we review recent progress on drivers and ecological impacts of tropical moist forest disturbances, and their monitoring and modeling methods. Disturbances in tropical moist forests are primarily driven by clearcutting, selective logging, fire, extreme drought, and edge effects. Compound disturbances such as fire and edge effects aggravate degradation in the edge forests. Drought can result in terrestrial carbon loss via physiological impacts. These disturbances lead to direct carbon loss, biophysical warming and microclimate change. Remote sensing observations are promising for monitoring forest disturbances and revealing mechanisms, which will be useful for implementing disturbance processes in dynamic vegetation models. Yet, constrained spatiotemporal coverages and resolutions limit the application of these data in process-based models. It is also challenging to represent physical processes derived from fine-resolution remote sensing data in coarse-resolution models. We highlight the need to continuously integrate new datasets and physical processes in forest disturbance modeling to advance understanding of disturbance patterns and impacts. Interactions and impacts of climate change and anthropogenic activities should also be considered for modeling and assessing feedbacks of tropical moist forest disturbances.

KEYWORDS

disturbances, tropical moist forests, deforestation, forest degradation, remote sensing monitoring, process-based models

1 Introduction

Tropical moist forests are one of the world's largest and most productive ecosystems and an important component of the global carbon cycle, containing 44% of the global aboveground biomass (Liu et al., 2015; Xu et al., 2021). Over the past decades, they have been affected by severe natural (e.g., drought, fire) and anthropogenic (e.g., deforestation, shifting cultivation, mining) disturbances, leading to substantial decreases in forest area, aboveground biomass, and soil carbon (Pugh et al., 2019a; Hansen et al., 2020; Pyles et al., 2022). Deforestation and forest degradation induced by these disturbances can destroy vegetation and reduce aboveground carbon stock, resulting in significant carbon emissions (Molinario et al., 2017; Wigneron et al., 2020; Ahmed et al., 2021). Nevertheless, carbon sequestration from post-disturbance ecosystem recovery remains limited in tropical moist forests at a regional scale due to soil carbon loss (Kleinschroth et al., 2015; Heinrich et al., 2023). Under intensifying climate change and human activities, disturbance-induced emissions will likely increase in the future (Dai, 2013; Li et al., 2017). Additionally, disturbances can harm vegetation health and vitality, lead to tree mortality, and threaten ecosystem services in the tropics (FAO, 2020). Studying disturbances in tropical moist forests is thus of great value in exploring physical mechanisms of disturbances, designing management and conservation policies, and mitigating climate change in the future.

Forest disturbances can cause forest loss and degradation. The extent, type, and impact of forest disturbances can be measured from field experiments, forest inventory data, and remote sensing observations. Field experiments such as the Biological Dynamics of Forest Fragments Project and the throughfall exclusion experiment were designed to study the effects of a particular disturbance type (Fisher et al., 2007; Laurance et al., 2011). Forest inventory data from the Food and Agriculture Organization of the United Nations (FAO) indicated a decrease in tropical deforestation rate from 15.8 Mha yr^{-1} during 1990–2000 to 10.2 Mha yr^{-1} during 2015–2020 (FAO, 2020). Recently, remote sensing data have been commonly used to investigate forest disturbances as multi-year products at moderate-to high-resolutions became available. For example, global forest loss data at 30 m resolution revealed that deforestation decreased in Amazon but increased in Indonesia during 2000–2012 (Hansen et al., 2013). Multi-year optical and microwave data also indicated that the total forest degradation area exceeded the deforested forests in the Amazon since the 1990s (Matricardi et al., 2020; Qin et al., 2021). However, there is still difficulty in monitoring forest degradation and its ecological impacts, preventing full understanding of its driving mechanisms and modeling development of the physical processes.

This review aims to present key findings from recent studies about the magnitudes, mechanisms, and impacts of disturbances in tropical moist forests. We first summarized the disturbances and their underlying drivers that lead to deforestation and degradation in pantropical moist forests, specifically focusing on the physical processes and mechanisms. We then evaluated the impacts of the disturbances on the carbon cycle, surface energy budget, and microclimate. We further discussed the data and modeling needs for studying these disturbances. In particular, we emphasized the integration of remote sensing data for representing related processes in dynamic global vegetation models (DGVMs).

2 Recent scientific advances in forest disturbances

2.1 Definitions and types of forest disturbances

In ecology, disturbance is commonly defined as regular or irregular events that disrupt the structure of an ecosystem, community, or population and alter the physical environment or resource availability (White and Pickett, 1985). Here we focus on the most common disturbance types in tropical moist forests (Figure 1). For anthropogenic types, we consider clear-cutting, selective logging, forestry, shifting agriculture (and related fire use), and edge effects induced by forest fragmentation. Wildfire and extreme drought are the major natural disturbance types reviewed in this article. Driven by natural climate variability and anthropogenic activities, forest disturbances typically result in substantial deforestation and forest degradation in the tropics. Deforestation refers to the transition of forests to other land cover types, such as forest clear-cutting for cropland (Curtis et al., 2018). Unlike deforestation, forest degradation leads to a loss of forest attributes (e.g., canopy cover, biomass) and a decrease in ecosystem functioning and services (e.g., carbon sequestration, soil protection, biodiversity), but the land cover type remains unchanged (Ghazoul et al., 2015; Zhu et al., 2023).

2.2 Driving factors of forest disturbances

Natural and anthropogenic drivers of forest disturbances vary across the tropics (Andoh et al., 2022). Long-term and permanent deforestation is typically caused by commodity production, urbanization, and mining, with forests converted into other land cover types such as agriculture, plantation, or infrastructure (Curtis et al., 2018; Giljum et al., 2022). Meanwhile, short-term forest loss is commonly associated with shifting cultivation, forestry, and fire. Forest degradation is mainly caused by forest fragmentation resulting from deforestation, forestry, overgrazing, uncontrolled fire, and extreme climatic events like drought (Kissinger et al., 2012; Zhu et al., 2023).

In Africa, increasing food and energy demands due to socioeconomic development and rapid population growth lead to deforestation and degradation (Rudel, 2013; Heinimann et al., 2017; Curtis et al., 2018; Tyukavina et al., 2018). Two major types of human activities have resulted in substantial forest loss: 1) widespread selective logging and the following constructions of roads and log landings (Kleinschroth et al., 2016; Umunay et al., 2019) and 2) fires for forest clearing induced by shifting cultivation or land management (Barlow and Peres, 2008; Dwomoh et al., 2019; Zubkova et al., 2019). Impacts of industrial mining in Africa are relatively minor except for Ghana, where direct forest loss from mining was 213 km^2 during 2000–2019. Charcoal collection as a local energy resource is another driver of deforestation and degradation in low-income regions (Balomba et al., 2018). In

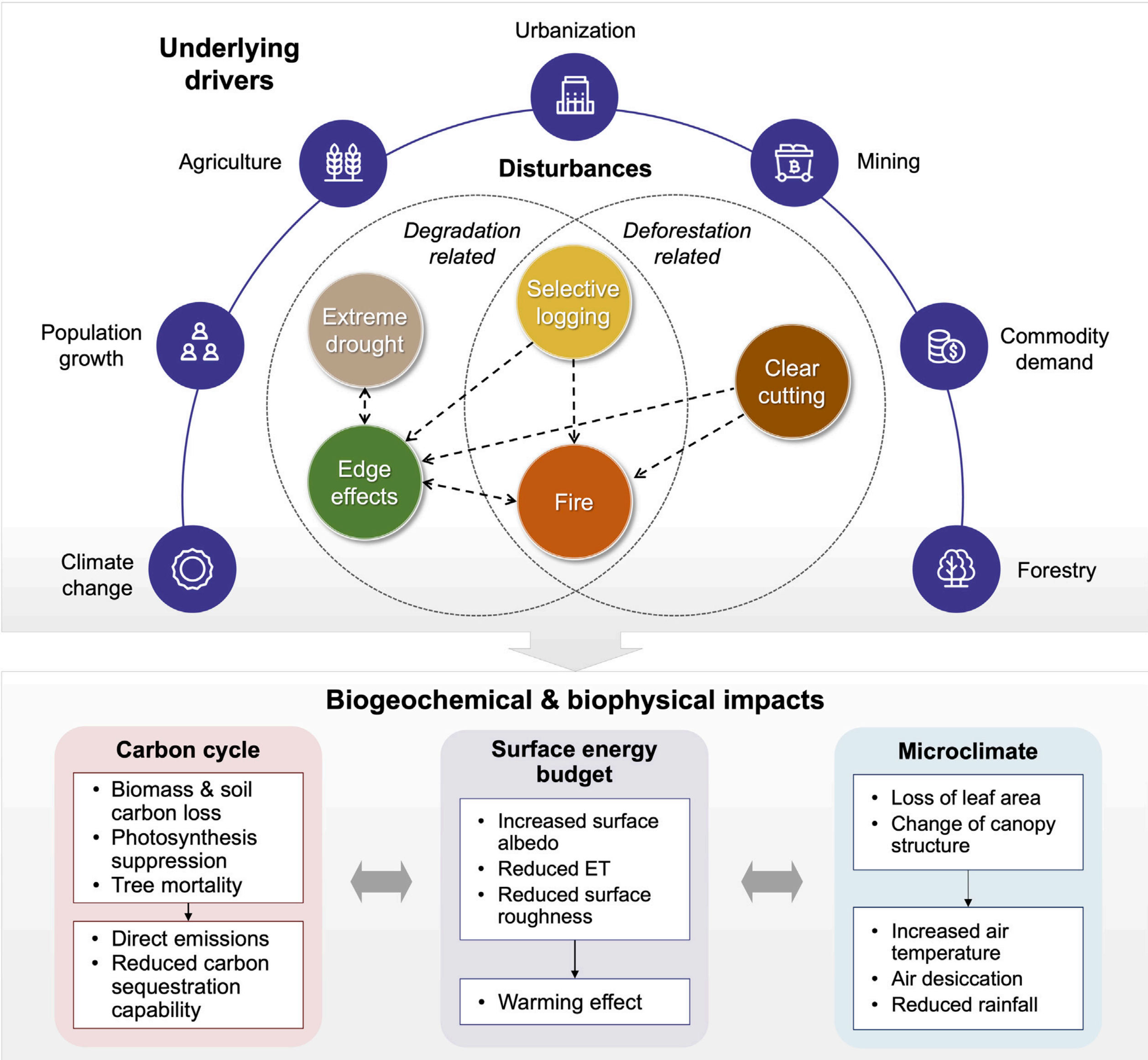

FIGURE 1
Types, underlying drivers, and biogeochemical and biophysical impacts of major disturbances in pantropical moist forests discussed in this review. The dashed arrows highlight potential interactions of compound disturbances. Forestry is included as a driver to represent natural forest loss induced by forestry commodities or plantations (e.g., oil palm, rubber). Here ET refers to evapotranspiration.

addition to human activities, extreme floods, droughts, and megaherbivores (e.g., elephant, hippo, rhino) have led to forest damages and become common natural disturbances in Africa in recent years (Wieczkowski, 2009; Parolin and Wittmann, 2010; Cromsigt and te Beest, 2014; Schmitz et al., 2018; Xu et al., 2019; Hyvarinen et al., 2021).

Commodity-driven clear cutting is a main driver of deforestation in South America. Lost forest area was likely converted to cropland or pastureland (Curtis et al., 2018). Over the past 2 decades, massive cropland (e.g., soybean, corn, sugarcane) expansion strongly drive deforestation in Brazil (Zalles et al., 2019; Song et al., 2021). Between 2005 and 2015, mining also led to 9% of forest loss directly and indirectly in Brazilian Amazon (Sonter et al., 2017). Edge effects from deforestation-driven fragmentation, fire, and extreme droughts are the main drivers of forest degradation in South America (Lapola et al., 2023). In particular, about 60% of the degraded forests in the Brazilian Amazon can be attributed to edge areas and isolated fragments of forests from 1992 to 2014 (Matricardi et al., 2020). During this period, a notable increasing fraction of the degraded forests is from the logged and burned area. The humid forests in South America have also suffered from severe droughts that lead to tree mortality and threaten the carbon sink (Lapola et al., 2023). Additionally, flooding has become a new disturbance agent that leads to tree mortality and decreased resilience in Amazon forests (Resende et al., 2019; Boulton et al., 2022; Bredin et al., 2022).

Southeast Asia (SEA) has one of the highest rates of deforestation and biodiversity loss globally (Felbab-Brown, 2013), primarily due to human activities such as palm oil production, agriculture, and logging (Wilcove et al., 2013; Curtis et al., 2018; Zeng et al., 2018). Oil palm and rubber plantation expansion are the principal drivers of deforestation in the insular SEA and mainland SEA, respectively (Jamaludin et al., 2022). Land use for oil palm plantations has quadrupled since 1980, and approximately 50% of oil palm expansion occurs in the forests in Indonesia and Malaysia (Koh and Wilcove, 2008). Over 2001–2015, oil palm plantations led to about 50.2 TgC yr^{-1} biomass loss in these two countries (Xu et al., 2022). Forests with high biomass density were particularly encroached by small-scale plantations after 2007 (Xu et al., 2022). Additionally, Indonesia has experienced 1,901 km^2 area of deforestation directly from industrial mining, which is the most affected country in the tropics (Giljum et al., 2022).

2.3 Physical processes and mechanisms

The natural and anthropogenic drivers of deforestation and forest degradation affect tropical moist forests through various physical processes. Compared to deforestation, forest degradation involves more complex processes and mechanisms (Bullock et al., 2020a; Pandey et al., 2020). In recent decades, small-scale deforestation (e.g., shifting cultivation and road construction) has led to severe forest fragmentation and a large amount of edge forests (Taubert et al., 2018; Umunay et al., 2019). Edge forests become degraded over time through edge effects: local circulation transfers moist air in edge forests to adjacent non-forest areas, resulting in higher temperature, stronger wind, and more severe drought in edge forests. Influences of edge effects can extend from forest patch edges to interior forests by about 110 m in tropical moist regions, and the forests experiencing the most severe degradation are typically located near the edges of forest patches (Broadbent et al., 2008; Laurance, 2008).

Fire is also an important driver of degradation in tropical moist forests, where trees are typically not resistant to fires. Compared with forests that have never suffered a fire, burned forests show reduced biomass and divergent vertical structures dominated by pioneers and saplings (Barlow and Peres, 2008). A positive feedback loop may exist between fire and edge effects in Africa: in edge forests with low humidity, it is easy for fires to intrude and burn the forests; fires also enhance the degradation of edges in tropical moist forests (Dwomoh et al., 2019; Zhao et al., 2021). However, under severe fires, tropical forests could experience substantial tree cover loss, become prone to burning, and eventually transform into savannas (D'Onofrio et al., 2018; Hoffmann et al., 2012). Fires can further interact with forest edge effects via two possible mechanisms: directly burning into forest patches and indirectly enhancing local circulation between edge forests and non-forest areas (Zhao et al., 2021). Such interactions of these compound disturbances will further worsen the degradation of edge forests in the tropics.

Widespread drought directly reduces terrestrial carbon storage via physiological impacts (Reichstein et al., 2013; Xu et al., 2019). Drought-driven soil water depletion and heat stress cause water deficit for plant uptake and affect tree growth and photosynthesis. Tree mortality induced by extreme drought then reduces terrestrial carbon sink (Brienen et al., 2015). During the 2010 drought, the Amazonian rainforest lost about 2.2 PgC carbon, even reversing it from a carbon sink to a source (Phillips et al., 2009; Lewis et al., 2011). Drought also has complex impacts on vegetation evapotranspiration. Decreased soil moisture and transpiration from stomatal closure under drought typically lead to suppressed evapotranspiration in tropical moist forests (Corlett, 2016). On the other hand, increased atmospheric moisture demand under drought may promote evapotranspiration, which can cause flash droughts and exert ecosystem stresses (Zhao et al., 2022). Additionally, drought indirectly impacts tropical forests by increasing the frequency and intensity of other disturbances, such as fire and edge effects (Staal et al., 2020; Numata et al., 2021). With more defoliation and litter accumulation, and drier vegetation components, it increases the vulnerability of moist forests to fires in Amazon (Asner and Alencar, 2010; Brando et al., 2014). The long-lasting legacy effects of drought cause continuous carbon loss and accelerate widespread forest degradation (Bullock et al., 2020a; Qin et al., 2021).

2.4 Biogeochemical and biophysical impacts

Disturbances substantially impact forest structure, vegetation composition, and biogeochemical cycles (carbon, nitrogen, phosphorus, etc.) in tropical moist forests (Ciais, 2013; Longo et al., 2020). Specifically, they cause direct loss of carbon storage via emissions and affect carbon sequestration capability, which may change the ecosystems from carbon sinks to sources (McLauchlan et al., 2014; Kranabetter et al., 2016). The changes in forest structure and carbon cycle, in return, can affect ecosystem resilience and disturbance regime. Here we only focus on the disturbance impacts on the carbon cycle in tropical moist forests. According to satellite data, carbon loss due to tropical deforestation was about 0.57–1.22 PgC yr^{-1} during 2000–2005, and South America, Africa, and Asia accounted for 54%, 32%, and 14% of the total loss, respectively (Harris et al., 2012). Another study found a similar magnitude of carbon loss (0.60–1.24 PgC yr^{-1}) in the 2010s by integrating field samples and satellite imagery (Achard et al., 2014). In comparison, estimations based on forest inventory data and a bookkeeping model delivered a considerably higher carbon loss of 2.94 PgC yr^{-1} during 1990–2007 from tropical deforestation (Pan et al., 2011). This difference is likely because forest inventory data are often collected from undisturbed forests with higher carbon densities. Also, bookkeeping models ignore natural disturbances and the impacts of climate and CO_2 on biomass, likely causing different results from satellite-based analyses. Compared to deforestation, carbon loss from forest degradation is relatively difficult to quantify since large-scale degradation monitoring is challenging. With commonly used data fusion methods and bookkeeping models, degradation-induced carbon loss was estimated to be 32%–69% of the total amount in tropical forests (Asner et al., 2010a; Baccini et al., 2017).

Tropical forest disturbances also result in biophysical warming by altering the surface energy budget. Deforested and degraded areas in tropical moist forests generally have lower evapotranspiration and surface roughness, thus having higher local surface temperature than the undisturbed forests (Li et al., 2015; Chen et al., 2020; Zhu et al., 2023). Although the albedo of deforested areas is higher than that of intact forests, the resultant cooling effect is more obvious in high-latitude regions with snow cover in winter (Lee et al., 2011; Peng et al., 2014). However, this effect is non-negligible in the tropics: complete tree cover loss from deforestation will increase the local land surface temperature by about 1.53°C from biophysical impacts (Alkama and Cescatti, 2016). In tropical moist forests, degradation could have a daytime warming effect of 0.78°C on the local land surface temperature, which is about 18% of that from deforestation (Zhu et al., 2023). Although the biophysical impacts of forest disturbances were found equally important as the biogeochemical effects, the underlying mechanisms are still unclear, and the biophysical effects are commonly overlooked by climate mitigation policies (Bala et al., 2007; Windisch et al., 2021).

Moreover, disturbance-induced deforestation and degradation can modify vegetation structure, species density, and distance to forest edge, leading to changes in microclimate conditions in tropical moist forests. Functioning as thermal insulators, forest canopies can adjust understory temperature and constrain extreme values of the microclimate (Jucker et al., 2018). Post-disturbance canopy loss drives temperature increase and air desiccation locally. In Malaysia, understory air temperatures in oil palm plantations and logged forests were about 6.5°C and 2.5°C warmer than those in primary forests (Hardwick et al., 2015). In addition to modifying forest structure, fragmentation in Amazonian rainforests can elevate tree-community dynamics (mortality, damage, turnover) near forest edges, further exacerbating edge effects on disturbance-sensitive species (Laurance et al., 1998; Ewers and Banks-Leite, 2013). Such impacts on microclimate can substantially affect the carbon balance, ecosystem functioning, and biodiversity in tropical moist forests (Vourlitis et al., 2004; Jucker et al., 2020; Sanczuk et al., 2023). Warmer and drier microclimate and leaf area reduction after deforestation may potentially convert transitional forests between tropical moist forests and savanna in Brazilian Amazon to be CO_2 sources in the future, by affecting forest respiration and canopy photosynthesis (Vourlitis et al., 2004). During extreme drought, the disruption of microclimate effects further intensifies forest mortality, impact evapotranspiration, and trigger a positive feedback loop that accelerates climate change (Au et al., 2022).

In recent years, compound disturbances have become an emerging issue for the degraded forests in the tropics. They exert multiplicative impacts on forest ecosystems from two or more combined disturbances, often by affecting the resilience to the subsequent disturbance during the recovery processes (Buma, 2015; Kleinman et al., 2019). Remote sensing observations reveal that the interactions between fire and edge effects aggravate degradation in the edge forests across Africa through fire intruding into forests (direct impact) and enhanced local atmospheric circulations (indirect impact) (Zhao et al., 2021). The aggravated degradation is mainly controlled by the direct impact in dry forests but mutually by both the direct and indirect impact in moist forests (Zhao et al., 2021). In Brazilian Amazon, the 2015 drought has led to increased fire occurrence in the degraded forests, resulting in substantial carbon emissions (Aragão et al., 2018). Compound disturbances from repeated fire, drought, and windstorms also result in prolonged forest degradation by impeding the recovery of carbon stocks and tree cover in southeast Amazon, according to multi-year field measurements (Brando et al., 2019). Nevertheless, our understanding of the ecological impacts from compound disturbances is still limited compared to individual disturbances (Graham et al., 2021).

2.5 Ecosystem recovery after disturbances

Recovery of secondary and degraded forests after disturbances is critical in ecosystem restoration, biodiversity conservation, and climate mitigation (Anderson-Teixeira et al., 2013; Poorter et al., 2021). Secondary forests (≤ 60 years) comprise approximately 28% of the forest area in Latin America (Chazdon et al., 2016). Over 1990–2019, only 13.5% of the deforested areas have been recovering after disturbances, with the largest proportion in Asia (Vancutsem et al., 2021). Though with less ecological values than primary forests due to the loss of biodiversity and habitat, these regrowing forests have a strong carbon sequestration capability that can potentially offset the carbon emissions from forest loss in the tropics (Poorter et al., 2016; Pugh et al., 2019b; Heinrich et al., 2023). After the extreme drought and heat from the 2015–2016 El Niño, moist forests typically did not recover to pre–El Niño levels pantropically by the end of 2017, according to aboveground biomass carbon estimated with remote sensing data (Wigneron et al., 2020). In contrast, long-term tree-level plot measurements of biomass carbon sink indicate that secondary tropical forests in drier climates were more vulnerable to the 2015–2016 El Niño event than the intact forests in South America (Bennett et al., 2023). Nevertheless, it can take up to a century for the biomass status and species composition to recover to those of the old-growth forests in the tropics (Poorter et al., 2021). Spatial variations also exist in forest recovery speed pantropically. In particular, intact tropical moist forests exposed to repeated past disturbances tend to have lower resilience and decreased recovery rate (Tao et al., 2022).

Forest recovery and resilience to disturbances can be quantified with forest attributes from multiple aspects, including soil properties, plant functions, and forest structures (Walker et al., 2010; Martin et al., 2013; Jamaludin et al., 2022). Chronosequence studies are the major approach to exploring forest recovery and resilience by reestablishing fire disturbance history and tracking the long-term forest properties (Cole et al., 2014; Poorter et al., 2016; Poorter et al., 2021). Site observations over the past 2 decades suggest high resilience of tropical forests to low-intensity land use change, with the forest attributes recovering to 78% of the old-growth states over 20 years (Poorter et al., 2021). In particular, biomass and species composition tend to recover much more slowly than other forest components, including structure, plant functioning, and soil. Recently, finer resolution and frequent satellite products provided a new opportunity for spatially-explicit representation of the recovery pace using multi-temporal observations (Wigneron et al., 2020; Xu et al., 2021) or a space-for-time method (Heinrich et al., 2021; Heinrich et al., 2023).

Recent studies have identified non-structural carbohydrates (NSC) as a crucial characteristic that controls the carbon balance and hydraulic processes of trees, further affecting forest resistance and resilience to disturbances (Hartmann and Trumbore, 2016; Fatichi et al., 2019). Its allocation strategies influence the growth and mortality of trees (Blumstein et al., 2022). For example, allocation to light-harvesting organs enables sufficient photosynthate, whereas more NSC allocation to storage can improve survivorship by providing a buffer against resource shortage when suffering disturbances but at the expense of growth. Conservative-growing species with larger NSC reserves and structural carbon inputs, therefore, are more likely to survive during extreme climatic events (Piper and Paula, 2020; DAndrea et al., 2021). Moreover, to maintain respiration and other metabolic functions, plants may eventually deplete stored NSC during the long-term disturbances (e.g., drought), resulting in increased mortality risk (Doughty et al., 2015).

3 Knowledge gaps and future research perspectives

3.1 Remote sensing observations

Satellite remote sensing is a primary tool to continuously monitor forest disturbances and quantify their impacts at a large scale in forest management and conservation practices (Lechner et al., 2020). Passive optical and microwave data have been widely adopted to map disturbances by tracking temporal changes in spectral information (Hirschmugl et al., 2017). Active sensors like Light Detection and Ranging (LiDAR) or synthetic aperture radar (SAR) provide high-quality data for assessing forest structure, canopy composition, and carbon sequestration potential (Mitchell et al., 2017).

However, limitations exist in forest disturbance research with remote sensing data. First, applications of such data are largely constrained by their spatiotemporal resolutions and coverages. Until recently, detecting small-scale disturbances or individual tree-level changes at a continental scale became possible by applying artificial intelligence (AI) to very high resolution (VHR) imagery (Brandt et al., 2020; Li et al., 2023). Yet, the low temporal resolution of the VHR data limits long-term monitoring of disturbances with time series analysis (Wang et al., 2019; Hethcoat et al., 2021). The effectiveness of optical products is also constrained by frequent cloud cover in the tropics (Hethcoat et al., 2021). Second, it is challenging to determine the causes of the disturbances and differentiate between natural or anthropogenic events purely based on remote sensing data (Stahl et al., 2023) such as lightning- or human-ignited fires. Third, primary and secondary forests may respond differently to disturbances regarding carbon sequestration abilities and ecological services (Gurevitch, 2022; Hua et al., 2022). Distinguishing their distributions and responses to disturbances is challenging at a large scale due to the complex information from heterogeneous canopy structures, species compositions, and within-canopy shadows (da Silva et al., 2014). Additionally, gradual forest changes induced by degradation may not be easily detectable using typical remote sensing techniques, making it difficult to monitor the legacy effects of degradation (Gao et al., 2020).

Satellite-based sensors have been newly launched or planned for data collection in recent years (Hwang et al., 2023). The combination of new optical, LiDAR, and SAR data has the potential to improve the characterization of forest disturbances and enhance our understanding of forest responses to disturbances. For example, observations from Global Ecosystem Dynamics Investigation (GEDI), the first spaceborne LiDAR sensor for monitoring global ecosystem structure, are utilized to quantify canopy structure and biomass and support monitoring of disturbances and their impacts on the carbon cycle (Dubayah et al., 2020). Though the GEDI data itself has limited spatiotemporal coverage, its integration with optical sensors (e.g., Landsat, Sentinel-2) provides wall-to-wall mapping of additional forest structure metrics (Potapov et al., 2021; Dwiputra et al., 2023). European Space Agency plans to launch the new “biomass” satellite carrying P-band SAR in 2024, which can capture the forest structure and help improve biomass and canopy height measurement. Meanwhile, newly developed products based on existing satellite data provide insights into disturbances and their impacts (Brandt et al., 2018; Fan et al., 2019; Xu et al., 2021; Santoro et al., 2021). Very promising AI approaches have been developed very recently, bypassing the problems of optical data saturation, by analyzing image texture in all spectral bands. Integrated with deep learning algorithms, recent studies have identified a surprisingly high quantity of trees and developed new benchmark datasets for tree cover and biomass in Africa utilizing multispectral VHR imagery from DigitalGlobe satellites (Brandt et al., 2020; Mugabowindekwe et al., 2023).

3.2 Integration of remote sensing data in model development

Development of remote sensing data can substantially support model development of tropical forest disturbances in several aspects. First, a major usage of remote sensing in DGVMs is to provide plenty of high-quality data for calibration and validation. Compared to field observations, remote sensing provides a wealth of continuous data in space and time. Products of aboveground biomass, gross primary productivity (GPP), leaf area index (LAI), and burned area have been widely adopted for calibrating and evaluating important model ouputs (Jung et al., 2011; Santoro et al., 2021). Second, satellite-based observations provide key forcing data for model simulation. Vegetation and land cover data provide plant functional type (PFT) maps and spatiotemporal deforestation information for DGVMs (Li et al., 2018). Burned area products are also critical for forcing historical forest disturbances induced by wildfires (Yue et al., 2014). Nevertheless, current application of remote sensing-based forcing data is limited to the contemporary period. Backcasting data before the satellite period can be improved by historical reconstruction (e.g., fire activity) based on contemporary remote sensing observations (Mouillot and Field, 2005; Yang et al., 2014) and machine learning methods. Third, abundant remote sensing data can be used to derive quantitative representations of physical and ecological processes related to forest disturbances (Figure 2). Currently terrestrial ecosystem models typically have very few representations of forest disturbances developed from limited field or experimental data for deriving the processes. With large spatial-temporal coverage, remote sensing data can summarize the general principles of the physical processes and thus improve the modeling capability of forest disturbance and the following recovery in DGVMs. For example, moderate-resolution (30 m) forest cover maps developed from Landsat data have been utilized to derive forest fragmentation metrics and analyze the fragmentation dynamics across the tropics (Taubert et al., 2018; Fischer et al.,

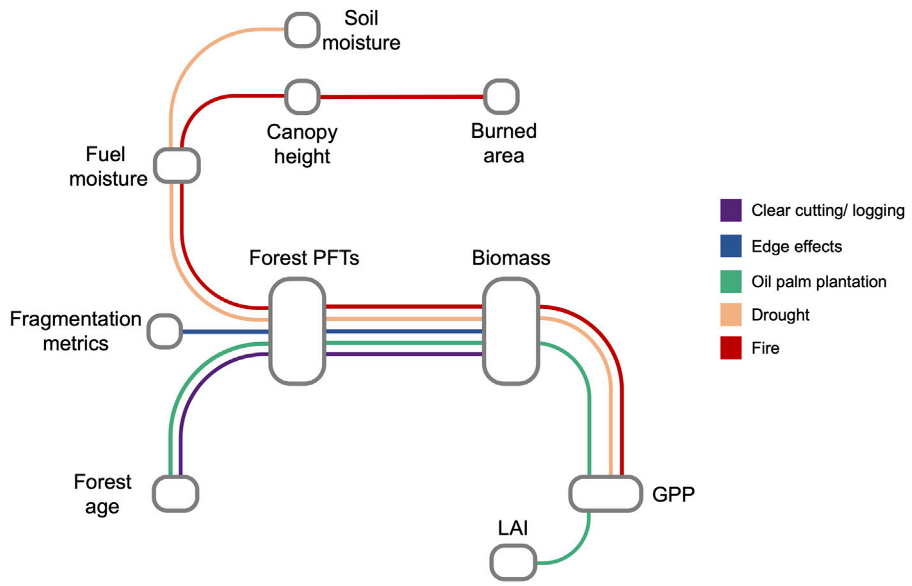

FIGURE 2
Remote sensing data that support the development of major forest disturbance modules in DGVMs. Here PFT, GPP, and LAI refer to plant functional type, gross primary productivity, and leaf area index, respectively. Each line represents a forest disturbance module developed in existing DGVMs. Each square represents a certain variable with satellite-based products that have been adopted in disturbance modeling.

2021). These results were further used to optimize the fragmentation model FRAG-B for simulating future patterns of tropical moist forests under different scenarios (Fischer et al., 2021).

Oil palm plantation is a typical example of deforestation and forest degradation in Southeast Asia (Vijay et al., 2016). Oil palm modeling has been implemented in DGVMs to simulate the carbon and climate impacts of land use change induced by oil palm expansion (Fan et al., 2015; Xu et al., 2021). For example, Xu et al. (2021) introduced an oil palm module in ORCHIDEE with specific morphology, phenology, and harvest processes for oil palm. They utilized 100 m global oil palm plantation maps developed from moderate-resolution (25 m) PALSAR observations to generate PFT forcing data integrating oil palm distribution. Satellite-observed GPP values were also used in model calibration due to the lack of site observations (Xu et al., 2021). Fan et al. (2019) reconciled a canopy interception scheme of oil palm into the Community Land Model. They found 18%–27% higher transpiration and 15%–20% higher evapotranspiration in oil palm plantations than in tropical forests. By monitoring oil palm plantations at higher spatial resolution (e.g., 10 m), it is possible to improve the simulation results by distinguishing industrial and small-holder oil palm plantations with different biophysical impacts (Meijide et al., 2017). The availability of high-resolution remote sensing products will thus improve our scientific understanding and modeling capability of tropical moist forest disturbances.

However, applying medium- and high-resolution (e.g., 30 m) remote sensing data for applications in coarse-resolution (typically 0.5°) DGVMs is challenging due to the mismatch in spatial resolutions and lack of sub-grid processes. Representing physical processes of small-scale disturbances in these models may lose substantial spatial details. One common solution is to resample the remote sensing data to the resolution of DGVMs. Yet, a lot of information from remote sensing data is lost. Another potential reason is the lack of sub-grid processes like forest demography representation in these models (Yue et al., 2018). Have proposed adding sub-grid variables and processes for estimating forest age cohorts to simulate net and gross land use change in a DGVM (ORCHIDEE). Therefore, it is necessary to address how to upscale variables and mechanisms derived from remote sensing data for applications in DGVMs. More work is needed to integrate sub-grid information in modeling small-scale forest disturbances such as degradation from forest fragmentation.

4 Perspectives of future research

Forest disturbance monitoring in the tropics can be improved in several aspects with the development of remote sensing. Near real-time monitoring can speed up the detection of forest disturbances and is now promising through the integration of multi-source time series data or VHR imagery. For example, the fusion of optical and SAR data from Landsat, Sentinel-2, and Sentinel-1 data has been found to be fast and effective in capturing tree losses in Amazon Basin (Tang et al., 2023). With a revisited time of 1-day, the VHR imagery (3 m resolution) from the PlanetScope nano-satellite constellation shows its capability to quickly identify forest disturbance activites (Francini et al., 2020). Active fire detections from the Visible Infrared Imaging Radiometer Suite (VIIRS) also support near real-time tracking and attribution of fire activities in the Amazon forests (Andela et al., 2022). Additionally, compared to abrupt forest loss, monitoring gradual forest changes due to degradation and recovery is still challenging due to their weak spectral signals (Gao et al., 2020). Spectral unmixing analysis with dense time series Landsat data has the capability to detect subtle forest changes from degradation in tropical rainforests in Rondonia, Brazil (Bullock et al., 2020b). More efforts should be made to develop suitable methods to accurately quantifying degradation extent at a large spatial scale. Monitoring forest disturbances with state-of-the-art datasets and methods can support the development of early warning systems for future research and decision-making.

Future work on developing satellite data products and physical processes is also critical to improve the modeling capability of tropical forest disturbances and enhance our understanding of the related mechanisms. Classification of forest disturbance agents at a large spatiotemporal scale is a prerequisite for developing disturbance models and quantifying ecological impacts. Though existing work has elaborated on classifying drivers of tree cover loss across the pantropical regions (Curtis et al., 2018; Laso Bayas et al., 2022), types and distributions of degradation drivers remain unknown. Continuous development of additional forcing data for contemporary and historical periods will also benefit disturbance modeling in DGVMs. Integrating NSC-related processes in DGVMs, such as species-based carbon allocation strategies and interactions between NSC, mortality and drought, may help address whether plants die of carbon starvation or hydraulic failure and support future projection of forest resilience under disturbances (Fatichi et al., 2019). Development of these processes also requires more field observations to understand their seasonal variations and unravel the underlying mechanisms of NSC. Moreover, although the compound disturbances may become more prevalent under climate change, explicit modeling of compound disturbances and forest degradation processes are still lacking in existing DGVMs.

Climate change has significantly altered the spatiotemporal patterns of extreme climatic events, affecting forest disturbances in the tropics. In recent decades, increasing frequency, severity, and duration of fire weather and drought have led to substantial carbon emissions in tropical moist forests (Dai, 2013; Jones et al., 2022). On the other hand, increasing atmospheric CO_2 may promote vegetation regrowth and forest recovery in the tropics (i.e., fertilization effects) via increases in water-use efficiency or biomass production, and contribute to carbon uptakes (Walker et al., 2021). Forests also respond divergently to extreme climatic events and fertilization effects as they differ in tree functional traits and species compositions (Anderegg et al., 2020). Tropical forest degradation has induced non-negligible biogeochemical and biophysical feedbacks on climate (Li et al., 2015; Liu et al., 2019; Zhu et al., 2023). Thus, future impacts of climate change and natural disturbances on tropical moist forests are still uncertain and should be further explored.

Moreover, anthropogenic disturbances in tropical moist forests are mainly driven by socioeconomic conditions and forest management policies (Rudel, 2013; Archibald, 2016; Zubkova et al., 2019). Combined with climate warming, human-induced deforestation (e.g., intensive agriculture, industrial logging) will severely degrade the tropical moist forests and reduce the resilience of vegetation and biodiversity in the future (Gardner et al., 2009; Asner et al., 2010b; Lewis et al., 2015). Over 2001–2018, such disturbances have led to more fragmented landscapes in tropical moist forests, with higher accessibility for further resource extraction (Hansen et al., 2020). Additional deforestation will severely increase the total number of forest fragments by 2050 (Taubert et al., 2018). Under a low mitigation scenario, burned area in Amazon forests is also likely to increase by 4–28 times by 2,100 (Le Page et al., 2017). Preventing new deforestation in Amazonia could reduce fire emissions by 36%–58% and avoid escaped fires into protected forests (Brando et al., 2020). Nevertheless, forest restoration and protection have the capability to mitigate these consequences and accelerate the carbon recovery in the tropics (Philipson et al., 2020; Koch and Kaplan, 2022). Social-economic development scenarios should also be incorporated in future research to understand human-climate interactions and their impacts on forest disturbances.

Author contributions

JH: Formal Analysis, Investigation, Resources, Visualization, Writing–original draft. WL: Conceptualization, Funding acquisition, Supervision, Writing–review and editing. ZZ: Formal Analysis, Investigation, Resources, Writing–original draft. LZ: Formal Analysis, Investigation, Resources, Writing–original draft. XD: Formal Analysis, Investigation, Resources, Writing–original draft. YX: Formal Analysis, Investigation, Resources, Writing–original draft. MS: Formal Analysis, Investigation, Resources, Writing–original draft. JZ: Formal Analysis, Investigation, Resources, Writing–original draft. PC: Writing–review and editing. J-PW: Writing–review and editing. RL: Writing–review and editing. GL: Writing–review and editing. LF: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Publisher's note

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