REVIEW SUMMARY

TROPICAL FOREST

The drivers and impacts of Amazon forest degradation

David M. Lapola*, Patricia Pinho, Jos Barlow, Luiz E. O. C. Aragão, Erika Berenguer, Rachel Carmenta, Hannah M. Liddy, Hugo Seixas, Camila V. J. Silva, Celso H. L. Silva-Junior, Ane A. C. Alencar, Liana O. Anderson, Dolors Armenteras, Victor Brovkin, Kim Calders, Jeffrey Chambers, Louise Chini, Marcos H. Costa, Bruno L. Faria, Philip M. Fearnside, Joice Ferreira, Luciana Gatti, Victor Hugo Gutierrez-Velez, Zhangang Han, Kathleen Hibbard, Charles Koven, Peter Lawrence, Julia Pongratz, Bruno T. T. Portela, Mark Rounsevell, Alex C. Ruane, Rüdiger Schaldach, Sonaira S. da Silva, Celso von Randow, Wayne S. Walker

BACKGROUND: Most analyses of land-use and land-cover change in the Amazon forest have focused on the causes and effects of deforestation. However, anthropogenic disturbances cause degradation of the remaining Amazon forest and threaten their future. Among such disturbances, the most important are edge effects (due to deforestation and the resulting habitat fragmentation), timber extraction, fire, and extreme droughts that have been intensified by human-induced climate change. We synthesize knowledge on these disturbances that lead to Amazon forest degradation, including their causes and impacts, possible future extents, and some of the interventions required to curb them.

ADVANCES: Analysis of existing data on the extent of fire, edge effects, and timber extraction between 2001 and 2018 reveals that 0.36×10^6 km^2 (5.5%) of the Amazon forest is under some form of degradation, which corresponds to 112% of the total area deforested in that period. Adding data on extreme droughts increases the estimate of total degraded area to 2.5×10^6 km^2, or 38% of the remaining Amazonian forests. Estimated carbon loss from these forest disturbances ranges from 0.05 to 0.20 Pg C year^{-1} and is comparable to carbon loss from deforestation (0.06 to 0.21 Pg C year^{-1}). Disturbances can bring about as much biodiversity loss as deforestation itself, and forests degraded by fire and timber extraction can have a 2 to 34% reduction in dry-season evapotranspiration. The underlying drivers of disturbances (e.g., agricultural expansion or demand for timber) generate material benefits for a restricted group of regional and global actors, whereas the burdens permeate across a broad range of scales and social groups ranging from nearby forest dwellers to urban residents of Andean countries. First-order 2050 projections indicate that the four main disturbances will remain a major threat and source of carbon fluxes to the atmosphere, independent of deforestation trajectories.

OUTLOOK: Whereas some disturbances such as edge effects can be tackled by curbing deforestation, others, like constraining the increase in extreme droughts, require additional measures, including global efforts to reduce greenhouse gas emissions. Curbing degradation will also require engaging with the diverse set of actors that promote it, operationalizing effective monitoring of different disturbances, and refining policy frameworks such as REDD+. These will all be supported by rapid and multidisciplinary advances in our socioenvironmental understanding of tropical forest degradation, providing a robust platform on which to co-construct appropriate policies and programs to curb it. ■

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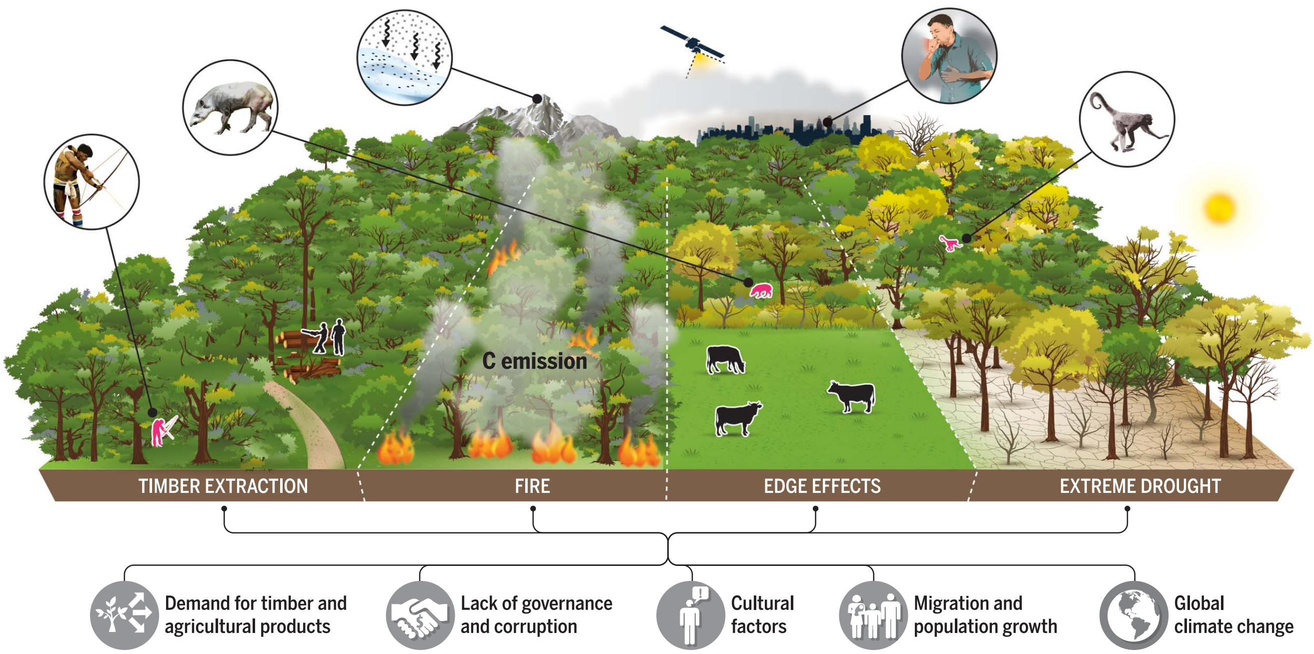

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An overview of tropical forest degradation processes in the Amazon. Underlying drivers (a few of which are shown in gray at the bottom) stimulate disturbances (timber extraction, fire, edge effects, and extreme drought) that cause forest degradation. A satellite illustrates the attempts to estimate degradation's spatial extent and associated carbon losses. Impacts (in red and insets) are either local—causing biodiversity losses or affecting forest-dweller livelihoods—or remote, for example, with smoke affecting people's health in cities or causing the melting of Andean glaciers owing to black carbon deposition.

REVIEW

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The drivers and impacts of Amazon forest degradation

David M. Lapola[1]*, Patricia Pinho[2], Jos Barlow[3], Luiz E. O. C. Aragão[4,5], Erika Berenguer[3,6], Rachel Carmenta[7], Hannah M. Liddy[8,9], Hugo Seixas[1], Camila V. J. Silva[2,3,10], Celso H. L. Silva-Junior[11,12,13], Ane A. C. Alencar[2], Liana O. Anderson[14], Dolors Armenteras[15], Victor Brovkin[16], Kim Calders[17,18], Jeffrey Chambers[19], Louise Chini[20], Marcos H. Costa[21], Bruno L. Faria[22], Philip M. Fearnside[23], Joice Ferreira[24], Luciana Gatti[4], Victor Hugo Gutierrez-Velez[25], Zhangang Han[26], Kathleen Hibbard[27], Charles Koven[19], Peter Lawrence[28], Julia Pongratz[16,29], Bruno T. T. Portela[23], Mark Rounsevell[30,31], Alex C. Ruane[9], Rüdiger Schaldach[32], Sonaira S. da Silva[33], Celso von Randow[4], Wayne S. Walker[34]

Approximately 2.5 × 10^6 square kilometers of the Amazon forest are currently degraded by fire, edge effects, timber extraction, and/or extreme drought, representing 38% of all remaining forests in the region. Carbon emissions from this degradation total up to 0.2 petagrams of carbon per year (Pg C $year^{-1}$), which is equivalent to, if not greater than, the emissions from Amazon deforestation (0.06 to 0.21 Pg C $year^{-1}$). Amazon forest degradation can reduce dry-season evapotranspiration by up to 34% and cause as much biodiversity loss as deforestation in human-modified landscapes, generating uneven socioeconomic burdens, mainly to forest dwellers. Projections indicate that degradation will remain a dominant source of carbon emissions independent of deforestation rates. Policies to tackle degradation should be integrated with efforts to curb deforestation and complemented with innovative measures addressing the disturbances that degrade the Amazon forest.

Tropical forests are critical for Earth's climate, biodiversity, local well-being and livelihoods, and humanity at large (*1*). They are also a hotspot for CO_2 emissions to the atmosphere, largely as a result of deforestation and other anthropogenic disturbances (*2*). Most analyses of land-use and land-cover changes in tropical forests have focused on the causes and effects of deforestation (*3*–*5*). However, other, less-well-studied anthropogenic disturbances also threaten the future of tropical forests. These disturbances include edge effects, selective logging, fire, and extreme drought, which have been intensified by human-induced climate change.

In the Amazon forest, the extent and long-term effects of such anthropogenic disturbances on the terrestrial carbon cycle, ecosystem functioning, and livelihoods of local populations are beginning to be understood and differentiated from deforestation impacts (*6*). These disturbances often co-occur and repeat multiple times and greatly increase the impact on forest condition and biodiversity (*7*). Many of the effects of these disturbances also occur over longer time scales. For instance, ongoing tree mortality after disturbance means that forests can continue to emit more carbon for decades after the disturbance (*8*, *9*), such that current estimates of the total carbon loss tied to degradation are comparable to, if not greater than, carbon loss from deforestation (*10*–*16*). Moreover, the reduced provision of ecosystem services resulting from such anthropogenic disturbances appears to disproportionately affect local livelihoods (*17*–*19*).

A recent study of the Amazon showed that only 14% of degraded forests were later deforested over a period of 22 years (*11*), suggesting that these are partially independent processes. Understanding and representing degradation as a process separate from deforestation is thus critical for improving observation networks, climate change and conservation policies, as well as modeling the resilience of the Amazon forest and its human populations, in light of ongoing land-cover and land-use changes and increased frequency of climate extremes.

In this Review, we (i) identify proximate and underlying drivers of disturbances related to pan-Amazon forest degradation; (ii) provide estimates of uncertainties in the total degraded forest area; (iii) assess the ecological impacts of degradation; and (iv) discuss the distribution of benefits and burdens among stakeholder groups. We then (v) examine our current ability to project Amazon degradation with existing data on disturbances and (vi) highlight the scientific advances required to understand and address forest degradation in Amazonia and other tropical forests.

Defining degradation and disturbance

Although many distinct definitions of forest degradation exist (*20*, *21*), for this Review we consider tropical forest degradation as a transitory or long-term (10^1- to 10^3-year time scale) deleterious change in forest condition. Condition includes functions, properties, or services such as, but not restricted to, carbon storage, biological productivity, species composition, forest structure, local atmospheric moisture, or uses and values of the forest to humans. Changes in forest condition can be determined through comparisons with a previous undisturbed baseline or inferred spatially using comparable undisturbed forests. Here, we focus on degradation driven by four human-induced disturbances (Fig. 1): extreme droughts, edge effects resulting from habitat fragmentation, timber extraction, and forest fires.

Extreme droughts have become increasingly frequent in the Amazon as land-use change and human-induced climate change progress (*22*), affecting tree mortality, fire incidence, and carbon emissions to the atmosphere (*23*–*25*). Deforestation leads to habitat fragmentation, including the edge, area, and isolation effects that are known drivers of changes in ecological condition (*12*, *26*). We focus mostly on edge effects, which are the changes in ecological and biophysical parameters that occur in forests adjacent to anthropogenic land uses (*9*). Timber extraction includes the legal and illegal selective logging that takes place in standing forests

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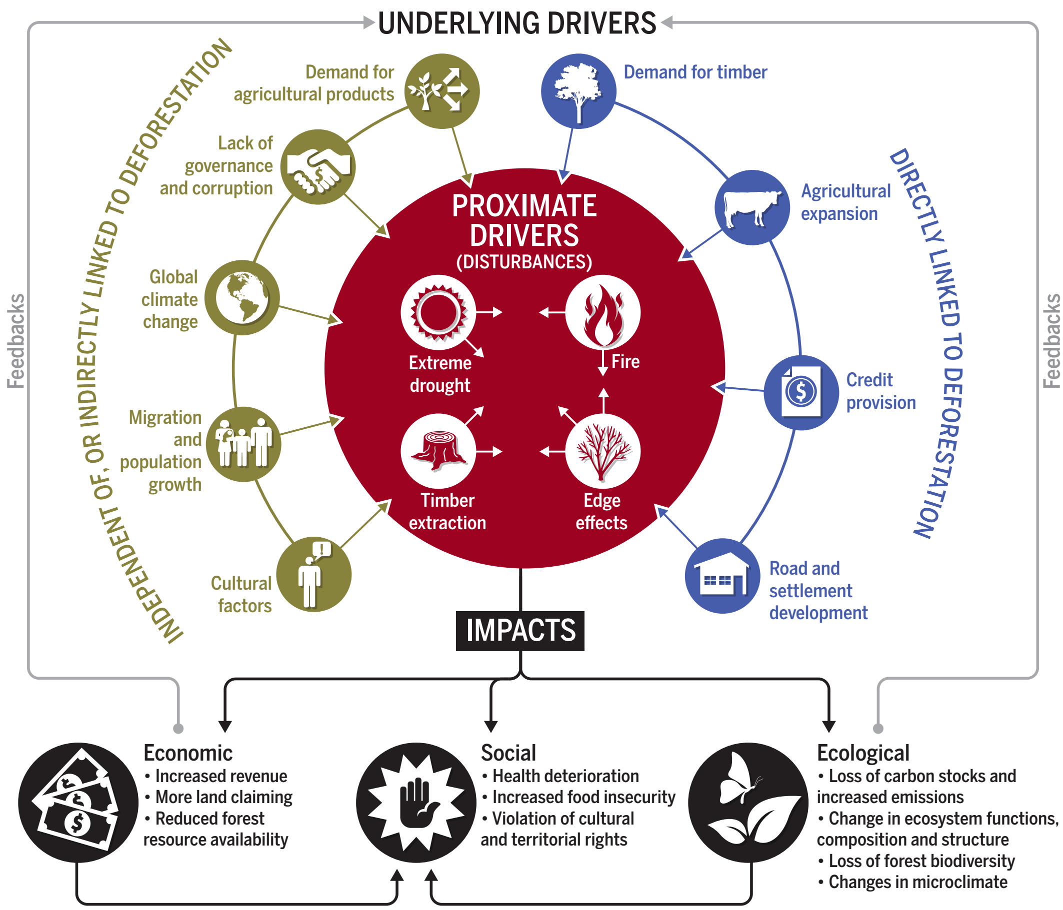

Fig. 1. A conceptual model of the drivers, impacts, and feedbacks of Amazon forest degradation. Some of the underlying drivers of disturbance (outer edge of the circle) are also directly related to deforestation processes (blue), whereas others are not (olive). The four main disturbances leading to degradation—extreme drought, fire, timber extraction, and edge effects—are intrinsically interrelated and can feed back to each other (see "Underlying drivers of disturbance" section). These disturbances cause economic, social, and ecological impacts that can be directly linked to each other (e.g., reduced forest resource availability leading to food insecurity). These impacts can also feed back to influence both the underlying and proximate drivers (respectively exemplified by revenue related to degradation causing local migratory movements and changes in microclimate causing increased fire incidence).

(*27*, *28*). Forest fires include all fires in standing forests (*29*); these cause degradation as Amazonian species have little or no evolutionary adaptations to fire. This list is not comprehensive; for example, heat stress, isolation effects, nontimber forest product extraction, and defaunation could all alter forest condition. However, the four disturbances that we focus on can all be studied across the Amazon by using available satellite data and image processing methods, and have the best-quantified links with forest structure and carbon stocks. We do not consider natural disturbances (e.g., blowdowns) to be degradation unless they interact with anthropogenic disturbances (*30*).

To evaluate degradation, it must be differentiated from deforestation. Conceptually, this is simple. Deforestation involves a change in land cover (e.g., loss of canopy cover to below a certain threshold) and generally a change in land use (e.g., from forest to agriculture or urban land use) (*31*). By contrast, whereas land use may or may not change during the process of degradation, land cover does not (i.e., forest remains forest). However, this conceptual clarity can break down when monitoring at scale. First, satellite-based monitoring of forests cannot easily discern changes in land use—areas affected by severe disturbances, such as thrice-burned forests, can be classified as deforested even though the land use has not changed. Second, some deliberate deforestation may be confused with degradation, with actors aiming to escape legal prosecution by using successive fires and other disturbances to gradually reduce tree cover over time. Although we do not attempt to integrate these nuances in this Review, future monitoring would benefit from considering four land-cover classes within the degradation-deforestation continuum: (i) undisturbed forest; (ii) degraded forest, where forest cover remains above a critical threshold and land-use change has not occurred; (iii) deforestation caused by successive or severe disturbances, where forest cover falls below a critical threshold of forest canopy structure but land-use change does not occur; and (iv) clear-cut deforestation, where forest cover falls below a critical threshold as a result of land-use change. Differentiating between the latter three classes is key for applying legal processes and can be supported by longer-term assessments, consideration of the geometric patterns of change (burned edges are rarely linear), and ground visits.

Underlying drivers of disturbance

The disturbances that cause degradation share a range of underlying drivers operating at the regional or landscape scale (e.g., lack of governance, presence of roads, or demand for local foods) or stemming from national or global influences (e.g., market demand for commodities, credit, and climate change) (Fig. 1). Many of these drivers are linked with deforestation (*5*). For example, agricultural expansion into forested lands increases the exposure of the

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remaining forests to edge effects, timber extraction, and the agricultural ignition sources that start many forest fires (32). Other key drivers of forest disturbance are, however, largely independent of the Amazonian deforestation process. Some timber extraction occurs in remote regions, far from the deforestation frontier; fires can extend deep into forested areas in drought years (25); and droughts are widespread across the basin (22, 33).

The underlying drivers of forest disturbance frequently co-occur and interact. Timber extraction, for instance, is driven by market demand but is facilitated by corruption and weak governance (34); forest fires are often caused by agricultural practices but can be exacerbated by extreme droughts (23). Furthermore, there are important and multiscale feedbacks between the drivers of disturbances and their impacts. At the landscape scale, deforestation or degradation-related disturbances cause warming and alter precipitation, potentially increasing drought (8, 35). At the global scale, carbon dioxide emissions from forest disturbance are major contributors to climate change, driving extreme droughts that cause or amplify degradation (24, 36). Anthropogenic disturbances in Amazonian forests are therefore the result of the interplay between a broad suite of drivers that are expressed and interact across a range of spatial scales (Fig. 1). Understanding their impacts is no less complex and requires quantifying the intensity and severity of disturbances and their distribution and interplay over time and space (Box 1).

Spatial extent and severity

Over the past decades, uncertainty in determining the extent of degradation (Box 1) has been minimized by advances in remote-sensing technology. The increased availability of time-series information from the Terra, Aqua (MODIS sensor) and Landsat (TM sensor) satellites has helped demonstrate the widespread occurrence and impact of tropical forest degradation (12, 15, 16, 37–39). The only existing pan-Amazonian direct estimate using a Landsat time series (11) indicates an area of 1,036,800 ± 24,800 km^2 affected by human and natural disturbances between 1995 and 2017 (47,127 ± 1127 km^2 $year^{-1}$), corresponding to 17% of the total forest area in 2017. Disentangling the spatial extent and severity of the multiple drivers of degradation is critical for understanding the impact of disturbances on tropical forests. Each disturbance type is driven by distinct factors, leading to great variation of their spatial extents from year to year. To capture the patterns of multiple disturbances, we compiled published data of the four main drivers of forest degradation, using the most up-to-date, spatially explicit datasets on burned area (40), timber extraction (41), edge effects (9), and drought (42). We assessed the period from 2001 to 2018. Data for the four disturbances had spatial resolutions of 0.5, 27, 0.03 and 55 km, respectively. We show that in that period fires alone affected 122,624 km^2, timber extraction 119,700 km^2, edge effects 188,531 km^2, and drought 2,740,647 km^2 (Fig. 2), representing, respectively, 1.8, 1.8, 2.8, and 41.1% of the remaining Amazon forest cover (6,673,908 km^2) (43).

Forest fires intensify during drought years (10, 23, 24, 44, 45), leading to acute peaks in burned area: 14,584 and 32,815 km^2 in the dry years of 2005 and 2010, respectively. This is two to four times the mean total forest area burned in all other years in the 2001–2018 period (7701 km^2). Although the extent of Amazonian fires during recent droughts has already been large, much larger megafires are also possible (46). Edge creation is strongly and positively correlated with deforestation at the basin level (9), although further deforestation could reduce the area of forests exposed to edges in regions with low levels of forest cover.

Despite remaining stable over time in the analyzed dataset, timber extraction extent remains highly uncertain. The product used here (41) shows an annual rate of 6623 km^2 $year^{-1}$ affected by timber extraction from 2001 to 2018 in the Brazilian Amazon. The first Brazilian Amazon–wide study estimated a rate of 11,537 km^2 $year^{-1}$ between 1999 and 2002 (27), which coincides with a period of high deforestation rates in the region. The other Brazilian Amazon–wide estimate assessing the extent of timber extraction from 1992 to 2014 showed an annual rate of 4479 km^2 $year^{-1}$ (12). This is 32% lower than the timber extraction estimate shown in Fig. 2, a difference that may be related to the frequency of the temporal series analyzed by Matricardi *et al.* (12), or the difference between the timber extraction product used here—which is based on national census statistics—and a remotely sensed approach. Estimates suggest that ~50% (or even more) of the timber extraction in the Amazon is illegal (47), meaning that this does not appear in either the national census or the product used here.

The complexity of quantifying degradation impacts increases with the frequency of overlap among different disturbances. Using the two highest spatial resolution datasets (burned and edge areas), we found that 25% of the total burned forest area was within 120 m of an edge, affecting 17% of the total edge area. Additionally, 6% of the area affected by both edges and fire was also affected by drought. Accounting for the spatial extent of forests hit by fire, timber extraction and edge effects, and the overlaps between them, the degraded area due to these three drivers affected at least 364,748 km^2 (5.5% of all remaining Amazonian forests) from 2001 to 2018. This corresponds to 112% of the total area deforested during this same period (325,975 km^2) (15, 48, 49), and is within the same magnitude of a previous estimate of degradation in the Brazilian Amazon of 337,427 km^2 in the 1992–2014 period (12). Estimating overlap between timber extraction and other drivers is not trivial because the data used for timber extraction provide a percentage cover by area within the 27-km-resolution grid cell, rather than a precise delimitation of the area affected by these events. Here, we assumed a proportional distribution of logged forests within the grid cell to account for the timber extraction overlaps with other drivers, as logged forests can be more flammable than undisturbed forests (50), and the extraction of timber is often associated with edges (51). Not all the extreme droughts observed in the Amazon

Box 1. Defining Amazonia's degradation regime.

The important factors determining impact can be understood by extending the concept of a fire regime to the disturbances that cause degradation.

Extent: The area of forest affected by disturbances. Severe disturbances that affect canopy cover can be assessed using remote sensing; more subtle changes resulting from droughts can be inferred from anomalies in water deficit (130) (see "Spatial extent and severity" section).

Intensity: A measure of the strength of a disturbance, such as logging offtake, fire radiative power, the strength of the water deficit anomaly, or degree of exposure to edges.

Severity: A measure of the impact of the disturbance on ecosystem-level or social conditions. This is a function of disturbance intensity and the sensitivity of the ecosystem or of societal groups that depend on forest resources.

Frequency: The number of disturbance events. The severity of disturbance often increases with the number of disturbance events, and recurrent fires or logging can bring about dramatic changes in ecological condition on decadal time scales.

Co-occurrence: The incidence of different forms of disturbance occurring in the same location (Fig. 2), in part encouraged by the interactions among them (see "Underlying drivers of disturbance" section). Co-occurring disturbances can amplify the severity (e.g., fire effects are more severe near edges). Co-occurrence can also be important at the landscape level, even if disturbances are not precisely superimposed. Their combined effect can contribute to significant losses of biodiversity (7) and of ecosystem services that are valuable to human populations (see "Social and economic dimensions" section).

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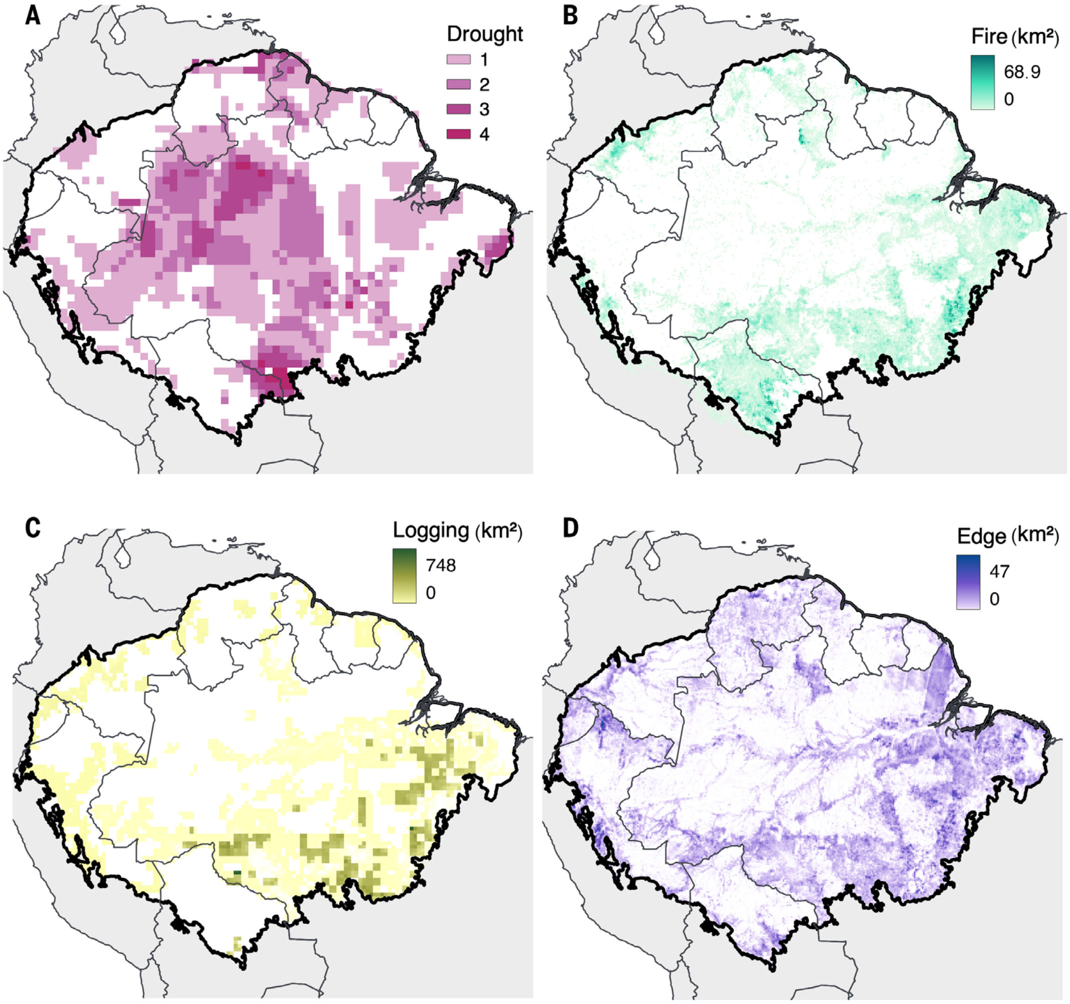

Fig. 2. Current (2001–2018) spatial distribution of the four main drivers of forest degradation in the Amazon forest, excluding deforestation and savanna areas. (**A**) Extreme drought occurrence, (**B**) burned area, (**C**) timber extraction, (**D**) area within a forest edge. The datasets employed (*23*, *40*–*42*, *129*), processing steps, and numerical estimates are shown in the supplementary materials.

in the analyzed 2001–2018 period have been unequivocally attributed to human-induced climate change (*22*). Nevertheless, when considering all the four main drivers, and all possible overlaps between them, the estimate of total degraded area increases to 2,542,593 km^2, or 38% of the remaining Amazonian forests. This total degraded area includes 628,909 km^2 of forest where two or more of the four disturbances overlap (table S1).

This assessment indicates a broad range of estimates, varying from 5.5% (considering only fire, timber extraction, and edge effects) to 38% (considering all four disturbances). Such a large range of estimates of the extent of degradation is mainly determined by the types of disturbances considered (with much larger area estimates if less-severe disturbances, such as droughts, are included; Fig. 2), the spatial and temporal ranges of the studies, and their distinct methods (*16*, *37*–*39*, *52*). All recent studies, however, consistently agree that the extent of degraded forest is growing, and the total area is either equal to or greater than the Amazon's deforested area (*10*–*12*).

Ecological impacts

Changes in carbon stocks and basin-wide emissions

Disturbance type and intensity are strong predictors of the magnitude of change in aboveground carbon stocks (i.e., severity; Box 1). Carbon losses are often greatest in burned forests, compared to the other disturbances (*53*). Sixty-nine percent of the burned area shown in Fig. 2 has been affected by a single understory forest fire, reducing aboveground carbon stocks by 13 to 50% (*17*, *54*, *55*) (Fig. 3). Tree mortality following understory fires varies spatially: The highest levels of tree mortality and the greatest biomass losses have been recorded in the Brazilian state of Pará (*29*, *56*). Smaller effects have been recorded in drier Amazonian regions (*44*) where trees are protected by thicker bark (*57*) and in less-seasonal regions where fire intensity may be limited by high fuel moisture content (*54*). Carbon losses in logged forests are also highly variable and range from 4 to 35% (Fig. 3), depending on extraction intensity and the management of collateral damage (*28*). The severity of edge effects varies in relation to the distance to the forest edge, with severity decreasing from the edge to the interior, and over time, with most losses occurring within 5 years of edge formation. Even when these factors are controlled, the impacts vary substantially: Carbon losses within 120 m of an edge range from 23 to 35% in the first 4 years after the edge formation (*6*, *26*), with the severity potentially related to exposure to fire (*9*) (Fig. 3). Edge effects may also vary over much larger spatial scales and could be less severe in forests on the richer soils of western Amazonia (*58*). Finally, extreme droughts bring about short-term carbon losses of 1 to 8% (*23*, *59*) (Fig. 3).

Time since disturbance is an important determinant of aboveground carbon stocks. When forests are burned, the recovery of carbon stocks from tree recruitment and growth is offset by

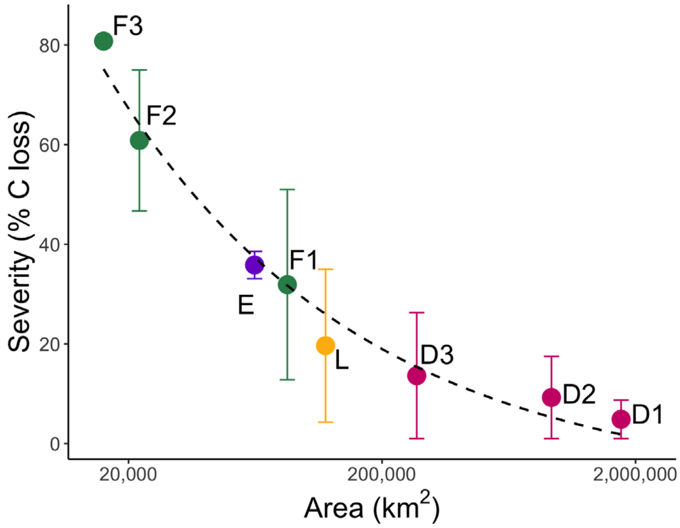

Fig. 3. The relationship between the area affected between 2001 and 2018 and disturbance severity (carbon loss). D, extreme drought; E, edge effects; F, forest fire; L, timber extraction (logging). Numbers denote single events (1) or repeated fires or droughts (2 or 3). Area is shown on a $\log_{10}$ scale. See supplementary materials for analysis methods.

high rates of ongoing tree mortality (*23*, *56*, *60*), such that burned forest can be a net source of carbon emissions for up to 7 years after the fire and hold ~25% less carbon after 30 years (*45*, *55*, *60*). Biomass recovery times after logging are almost directly proportional to the volume of timber extracted, such that extraction of 10, 25, or 50% of prelogging aboveground carbon stocks would require 12, 43, or 75 years to recover (*28*). These rates also vary across the Amazon, depending on soil fertility and climate (*50*). Carbon losses from edge effects are most pronounced after the first 4 years (*9*, *26*). As 66% of current edges are older than this (*6*), most will have incurred these losses. Longer-term assessments of drought impacts show mixed results, with plot-based studies reporting both rapid recovery (*61*) and sustained effects lasting at least 3 years (*23*).

Repeated disturbances are often associated with the greatest losses of aboveground carbon. Recurrent fires can lead to losses of over 80% of aboveground carbon (*17*) (Fig. 3), which is important as almost one-third of the burned area has been burned either twice (18%) or three or more times (13%) (Fig. 2). Similarly, the impacts of timber extraction are far greater in forests that have suffered multiple extraction events (*53*), and edge effects are greater when forests are exposed to multiple edges (*62*). The cumulative impact of multiple droughts on aboveground carbon is not known but could be important given that over one-third of the drought-affected area was affected by two (26%) or more (10%) events in an 18-year period (Fig. 2). Co-occurring disturbances can also amplify effects, with windstorms resulting in much higher biomass losses in thrice-burned forest (31%) than in unburned forests (15%) (*30*).

Our overview of the extent (Fig. 2), severity (Fig. 3), and longevity of these four disturbances demonstrates that they are likely to be a substantial source of long-term carbon emissions from Amazonian forests. However, at present there is insufficient information on disturbance recurrence and recovery to make a reliable estimate of their combined influence on the Amazon's carbon balance. Studies that have attempted this using remote sensing, or mixing field assessments with estimates of extent, estimate annual emissions of between 0.05 and 0.2 Pg C year^{-1} for a different combination of disturbances (*10*–*16*), which are comparable to deforestation emission estimates of 0.06 to 0.21 Pg C year^{-1} (*49*, *63*). Yet comparisons remain confounded by the different spatial and temporal scales of assessments and the different types of disturbance that are being assessed—studies inferring degradation from canopy openness are likely to miss some of the degradation resulting from edges or low-intensity logging, while airborne air sampling is unable to accurately separate emissions from deforestation and degradation (*8*).

Other climate processes

Beyond carbon, forest disturbances influence a range of atmospheric processes. Within the forests themselves, tree mortality from forest fires, timber extraction, and edge effects increase temperatures and lower the humidity of the understory (*26*, *29*, *35*, *50*). Reductions in forest biomass and changes in species composition also affect water cycling (*64*). Forest edges generate 5% less evapotranspiration (ET) than forest interiors (*65*), and degraded forests provide between 2 and 34% less ET than intact forests in normal dry seasons, with stronger reductions in southern drier sites (*35*). However, the magnitude of change for ET seems to be far less than that for carbon stocks (*35*, *66*), with recovery occurring within 7 years of repeated forest fires (*66*). Amazonian fires also reduce air quality many thousands of kilometers from the source (*67*), while soot deposits are accelerating glacier melt in the Andes (*68*).

Biodiversity and ecosystem functioning

Fires, timber extraction, and edge effects reduce the number of forest species (*7*, *69*) and species with the highest conservation values (*7*). In landscapes with ~80% forest cover in the eastern Amazon, the combined influence of forest disturbances in remaining forest results in about as much biodiversity loss as the loss of habitat in the deforested areas (*7*). In fragmented landscapes, patch area is an important determinant of species persistence; conserving the full suite of forest birds requires maintaining large patches (e.g., >10,000 ha) of good-condition forest (*70*). The impacts of forest disturbance extend to aquatic biota, and even reduced-impact logging affects the composition and functional traits of stream fishes (*71*). Disturbance also disrupts multitrophic processes such as pollination, decomposition, seed dispersal, and herbivory (*72*) and drives sublethal changes in the morphology or physiology of birds (*73*) and dung beetles (*69*).

The postdisturbance recovery of forest fauna can be slow, and understory forest-specialist birds do not recover their original abundances even 10 years after a single fire event (*74*). Recovery can be further impeded where forests have been affected by previous disturbances (*72*) or where succession is dominated by lianas, palms, bamboos, or invasive grasses (*45*, *75*). Finally, fauna can support postdisturbance forest recovery, with birds, terrestrial ungulates, and primates all helping disperse seeds (*76*). Some of these taxa are resilient to low-intensity disturbance (*77*) and contribute to forest regeneration where hunting is controlled and there is connectivity with undisturbed forests (*78*).

Social and economic dimensions

Whether initiated by chainsaws, fire, or drought, people drive forest degradation (*21*). Its prevalence and persistence (Fig. 2) are largely explained by the (short-term) economic benefits driving the four disturbances (Fig. 4A). A broad range of human actors generate these disturbances, from local forest communities that use fire for subsistence agriculture, regional commercial businesses extracting timber, to distant city-dwellers consuming commodities originating in forest landscapes, the fossil fuel consumption of the international community, and investment banks contributing to geopolitical and market forces (*79*). These actors are influenced by the outcomes of disturbances (e.g., smoke from fires), and the resulting degraded

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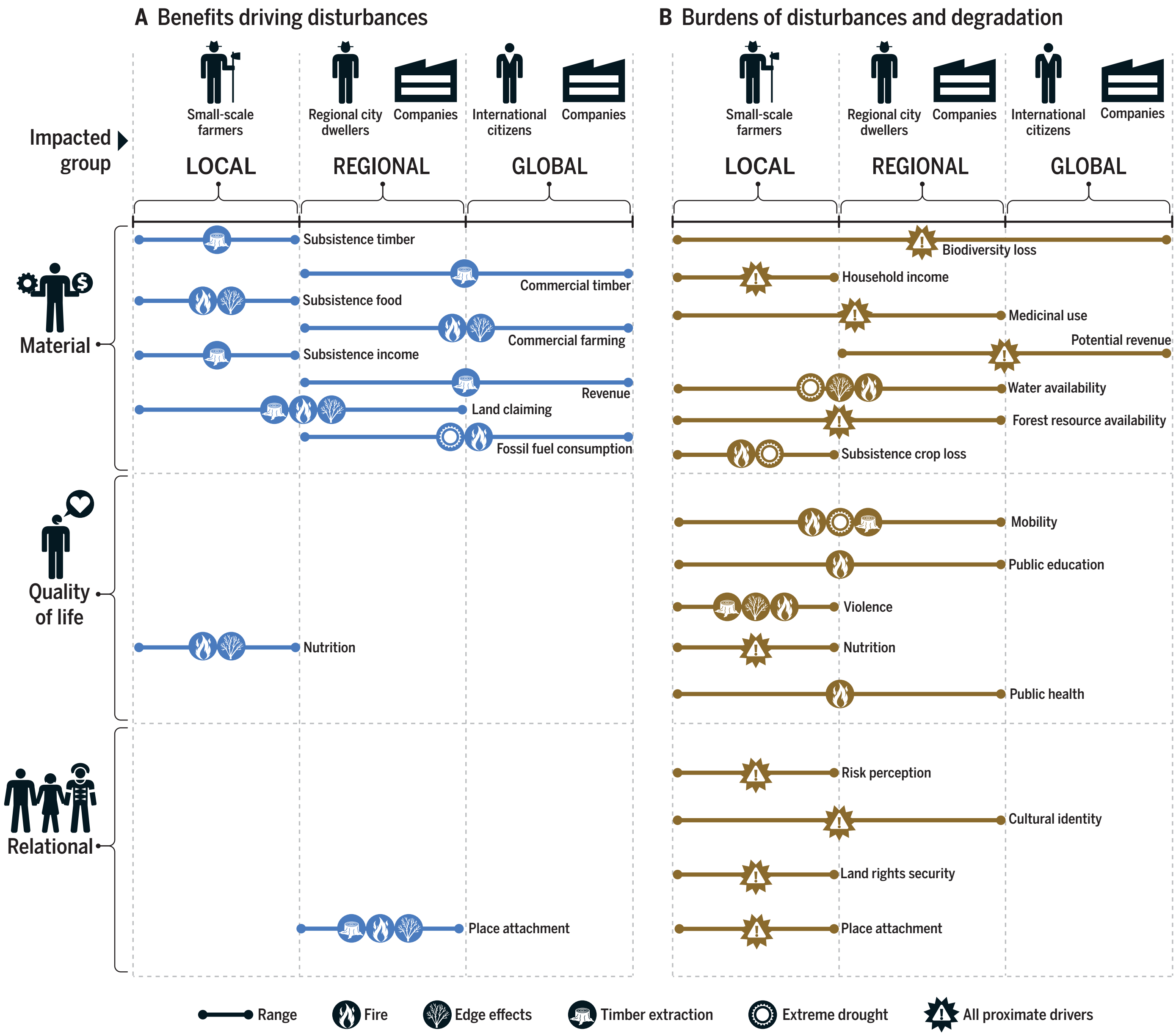

Fig. 4. Socioeconomic benefits and burdens of Amazon forest degradation and its drivers are unevenly distributed. (**A**) The underlying drivers of disturbance generate mainly material benefits, while (**B**) the resulting forest degradation generates burdens that are unevenly distributed among stakeholders and across scales. Impacts are displayed as benefits (blue) and burdens (brown) to people, with drivers and outcomes grouped according to material, quality of life, and relational dimensions. The main disturbance type(s) associated with each outcome is indicated by the icon and the range of impacts by the horizontal extent. This list is not exhaustive.

forest states, in distinct [i.e., material, subjective (quality of life), and relational impacts] and unevenly distributed ways across multiple spatial scales (Fig. 4). Crucially, the flow of benefits (which are related to proximate drivers of forest degradation) and burdens (which are related to degradation outcomes) is misaligned. Benefits often accrue to external stakeholders, whereas burdens are concentrated locally, creating socioecological injustices (Fig. 4B). To achieve more just and sustainable outcomes, the benefit seeking that ultimately drives degradation needs to be balanced against the multitude of burdens that arise from it.

Material benefits of degradation

Many of the disturbances driving degradation deliver material benefits (i.e., money and goods) to privileged elites living outside of forest landscapes (*80*, *81*). For example, a small fraction of (large-scale) landholders account for most forest loss (*82*), contributing to degradation via edge creation through deforestation, escaped pasture renewal fires (*32*), and reduced regional rainfall (*8*) and ultimately contributing to global climate change itself via carbon emissions (*83*). Forest loss is strongly associated with commodity production, with material benefits accruing to wealthy regional and international actors (*84*). For instance, even omitting the sizable clandestine market (*34*, *47*), timber extraction in the Brazilian Amazon generated US$459.5 million in 2018 (*85*), which was not well distributed (*4*).

At local scales, small-holder farmers contribute to forest degradation, either directly through small-scale timber extraction or hunting, or indirectly via agricultural fires that may escape into forests. Notably, benefits of local drivers are retained locally (e.g., supporting household incomes) or regionally (e.g., food security) (86) (Fig. 4A). Other benefits accruing locally include income from hired labor in logging camps (87). However, these economic benefits tend to be short term (4), poorly negotiated, and disproportionately small and do not compensate for the local damages that forest disturbances inflict (88, 89).

Multidimensional burdens exacerbate the vulnerabilities of marginalized groups

Forest disturbances driving degradation create burdens to multidimensional human well-being that are predominantly concentrated on local communities (Fig. 4B). The most severe material impacts are borne by small-scale farmers, Indigenous people, and traditional communities who rely on a diverse set of forest resources to underpin resilient livelihoods and cultural practices (90). Timber extraction reduces the availability of species that contribute to nutritional diversity or provide oils or medicines (89, 90). Reductions in diversity of host species undermine the "dilution effect" (where low-quality host abundance buffers parasite dispersal), increasing vector-borne diseases (e.g., Chagas disease) (91). The dense understory of fire-affected forests makes hunting harder (mobility in Fig. 4B) and reduces availability of preferred game species (92). Forest disturbances related to degradation can alter fish abundance in streams, rivers, and floodplains, with implications for the nutritional diversity and food security of local communities (71). Some of the material changes extend beyond local communities, as reductions in forest resources can affect peri-urban households that maintain strong links with forests (88), compounding existing vulnerabilities associated with structural marginalization (93).

Although less well understood than material impacts, burdens related to forest disturbance also affect the relational and subjective dimensions of people's lives, which make important contributions to human well-being (94). Further, some of the disturbances that cause degradation (e.g., burning, presence of logging operations) themselves reduce the quality of life of local peoples—for example, by increasing the exposure of forest peoples to infection (e.g., COVID-19) (95). Public-health burdens accrue from the smoke associated with fires and include premature deaths as well as school closures that potentially reduce the learning lifetime of local children (public education in Fig. 4B) (67, 96, 97). Incidence of violence rises when land conflicts associated with forest degradation occur (98), and within temporary settlements created for logging operations (99).

The loss of forest resources following disturbances can negatively influence relational dimensions of people's lives, including sociocultural reproduction, cohesion, and cultural practices. For example, forest degradation can erode communal sites, impair place attachments, and affect interactions with the forest and ways of knowing and of using its resources. Degradation can also heighten perceptions of vulnerability and risk owing to place dislocation, transformation, and threat of potential resettlement (100).

Diffuse and indirect burdens accrue to external actors

Amazon forest disturbances that drive degradation also burden regional and international actors, though often in more indirect and diffuse ways. For instance, people living large distances from forests may be affected by disturbance-induced changes in the carbon and water cycle (35). These impacts extend to regions surrounding the Amazon, with implications for material gains and revenue within the agriculture sector (83). Fires can influence the sustainability of water availability in distant (e.g., Andean) cities, with the deposition of black carbon accelerating glacial melt (68). Fire also causes material damage to the timber sector, affecting commercially unexplored forests (17, 101), and other losses to potential revenue and to the region's economy (e.g., through airport closures) (96).

Forest degradation precludes discovery of new pharmaceutical, nutritional, and bio-based products and can precipitate the emergence of pandemics with global consequences for health, economies, and well-being (102, 103). Further, the relationship between ecosystem degradation and regional public health has the potential to be important (104). Estimates suggest that the loss of ecosystem services as a result of extreme climate change in the Amazon may induce regional economy losses of US \$7.7 trillion in a period of 30 years (18), and this excludes the substantial intangible relational and quality-of-life impacts. Better understanding of the multifaceted suite of burdens extending from degradation across scales could help to inform appropriate policy responses and galvanize support in society for a shift toward more sustainable use of the forest.

Projecting Amazon forest degradation

Most studies assessing future scenarios for the Amazon focus on deforestation and its relationship with prospective road development, agricultural expansion, and conservation policies (3, 105–108). Only five studies have projected future Amazon forest degradation in a spatially explicit way, either covering the entire Amazon biome (109) or focusing on the Colombian (110), Brazilian (111, 112), or southern Brazilian Amazon (44). Modeling approaches include mechanistic (111), statistical (110, 112) and hybrid (44, 109) methods. Studies assessing the proximate causes (Fig. 2) focused on fire occurrence driven by deforestation and climate change (44, 109), fire intensity driven by climate change (111), edge effects due to forest fragmentation (110), or mixed causes (112). Two further studies modeled degradation in a nonspatially explicit way using fixed degradation-to-deforestation ratios (113) or statistical relationships of carbon loss caused by logging and fire (114). Despite the variation in methods and study areas, these modeling studies reinforce many of the findings emerging from empirical studies, including that (i) feedbacks between different drivers are key for Amazon forest degradation (109); (ii) degradation can occur independently from deforestation [e.g., control of deforestation can reduce fire activity, but only under weak to moderate climate change scenarios (109)]; (iii) climate change can boost fire intensity and ignition sources, promoting fire-driven degradation (111); (iv) roads promote degradation as well as deforestation (51); and (v) carbon dioxide emissions from degradation can overwhelm those from deforestation (44, 110), and the carbon uptake from regeneration (113).

Combining previously published projections of the individual main disturbances that cause degradation (43), we project potential future patterns of degradation of the Amazon forest and their effects on carbon stocks under two alternative deforestation scenarios: "governance" (GOV) and "business-as-usual" (BAU). These projections show (Fig. 5) that halting deforestation, as pledged by Amazonian nations in the Glasgow declaration and in their nationally determined contributions to the Paris Agreement, does not necessarily curb degradation across the Amazon. Projected 2050 annual carbon emissions are 0.06 Pg C $year^{-1}$ in the GOV scenario and 0.42 Pg C $year^{-1}$ in the BAU scenario. This upper limit is considerably higher than the upper limit of 0.2 Pg C $year^{-1}$ observed in the 2001–2018 period, owing to a stronger contribution of more frequent droughts in the future, but still lower than another projection restricted to the Brazilian Amazon (112). Indeed, the degradation-to-deforestation ratio for carbon emissions remains high both in a scenario where illegal deforestation is stopped after 2030 (GOV, 1.04) and in the BAU scenario, which extrapolates the land-use dynamics of the early 2000s (BAU, 0.74). To some extent, these findings are to be expected, given that halting deforestation leaves a larger forest area that is subject to fires, logging, or droughts (115). However, our assessment also indicates the importance of designing and implementing intervention strategies that address degradation and deforestation as distinct processes (116, 117).

Emissions in the GOV scenario are dominated by fire (59%), followed by droughts (38%) and logging (3%). However, in the BAU scenario, under Representative Concentration Pathway

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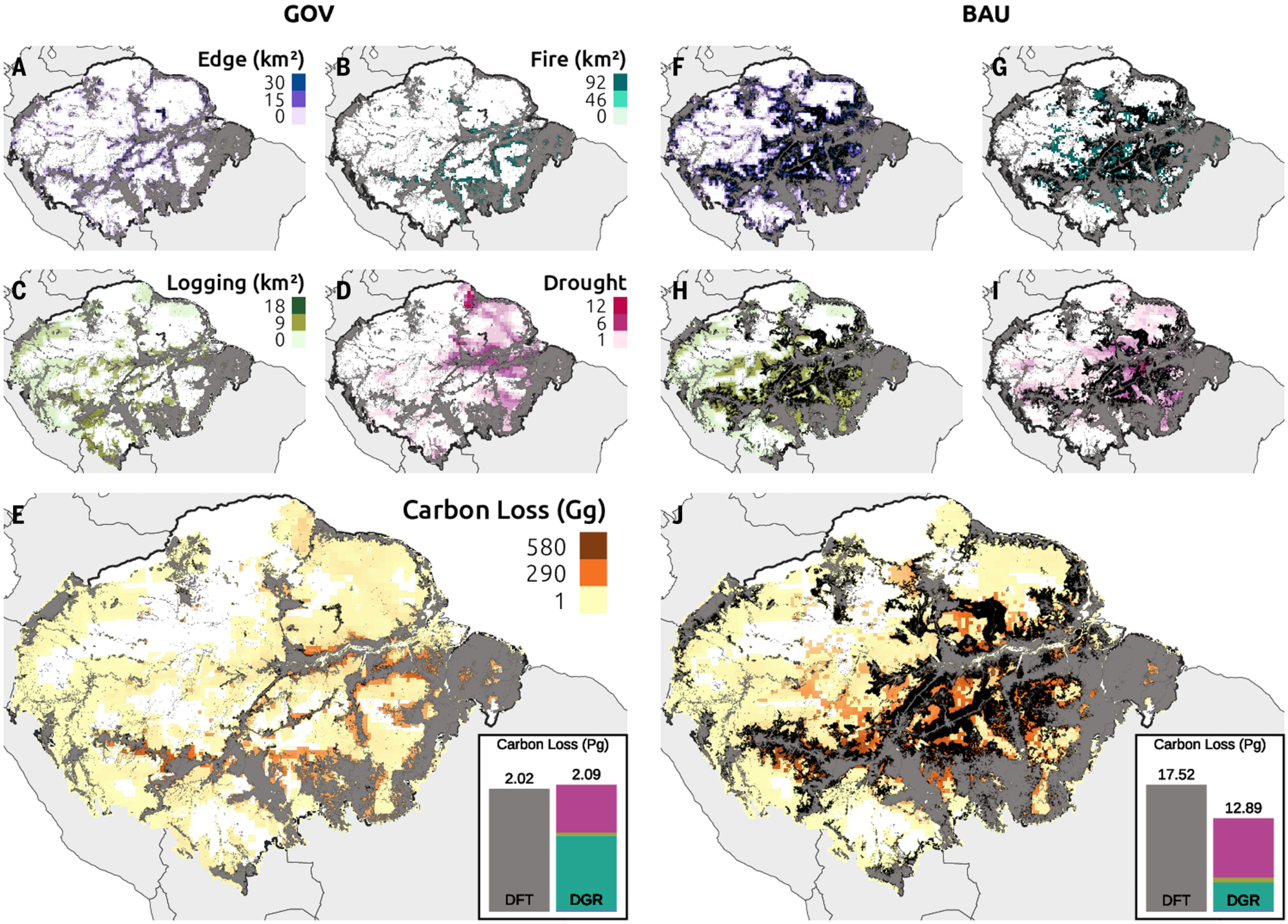

Fig. 5. First-order 2050 projections of Amazon forest degradation through its main drivers. Projections of 2019–2050 changes in the main proximate drivers of Amazon forest degradation. (**A** and **F**) Edge effects (*108*); (**B** and **G**) fire occurrence (*111*); (**C** and **H**) timber extraction (*41*); (**D** and **I**) extreme drought (in number of occurrences in 2019–2050) (*33*); and resulting combined carbon losses (**E** and **J**) under climate and deforestation governance (GOV) and business-as-usual (BAU) scenarios (*43*, *108*). Inset charts in (E) and (J) show resulting carbon emissions in the 2019–2050 period resulting from deforestation (DFT) and degradation (DGR) (notice the different scales). The share of C emissions per driver is shown in the DGR bar and follows map colors. Black map areas denote deforestation in the 2019–2050 period, whereas gray areas depict deforestation prior to 2019. See supplementary materials for methods and numerical results.

(RCP) 8.5 climate, droughts become the dominant cause of carbon emissions associated with degradation (63%), followed by fire (30%) and logging (5%). The high relative contribution of drought demonstrates that the mitigation of Amazon forest degradation also depends on concerted international (i.e., extra-Amazonian) efforts to abate global climate change. These findings are aligned with observational data regarding the hierarchy of each disturbance in terms of carbon loss and affected area (Fig. 3 and table S2).

Although these projections demonstrate the potential importance of future degradation, they have probably been underestimated as they do not include feedbacks and interactions between disturbances (see "Underlying drivers of disturbance" section). For example, degradation from timber extraction, extreme droughts, and edge effects alter the forest microclimate, making future fires more likely (*29*). The feedbacks between Amazon forest degradation and regional climate change are particularly relevant for determining the likelihood of an Amazon tipping point (*118*, *119*).

Degradation and the future of the forest

Although our understanding of degradation has improved markedly, important uncertainties remain regarding the quantification of the area affected by the different disturbances, their longer-term impacts, and how disturbance severity is modified by co-occurrence, repeated events, or changes in management practices (e.g., toward integrated fire management, or sustainable logging protocols). Our understanding of the drivers of disturbance would be improved by more in-depth analyses of underlying causes and better identification of the actors and funding chains, as has been extensively investigated for deforestation (*3*–*5*, *82*). Further, research is essential into what forms of governance, co-responsibility, and valuation can best, and most realistically, balance the environmental, social, and economic imperatives associated with forest resource management (*120*, *121*).

From the policy perspective, the distinct nature of proximate drivers, the range of stakeholders that benefit from them, and the challenges in monitoring disturbances all make curbing forest degradation considerably more complex than reducing deforestation. The Reduction of Emissions from Deforestation and Degradation (REDD+) framework is the only existing international policy mechanism that aims to address tropical forest degradation (*6*). Nevertheless, only a small minority of REDD+ projects are targeted at preventing degradation (*117*), and the identification of key actors and drivers in REDD+ projects is confusing, even when those address the well-known process of deforestation (*122*). Moreover, although leakage effects (displacement of deforestation from a REDD+ covered area to another area not covered by that program) are a major concern for deforestation-based projects (*123*), they remain unquantified for displaceable disturbances such as timber extraction.

Although our intent here is not to be policy prescriptive, this Review has nonetheless revealed some key priorities for policy-makers and practitioners. Preventing further deforestation remains a key objective for stabilizing the climate system, preserving biodiversity, and ensuring sustainable development; deforestation is itself a major driver of greenhouse gas emissions and biodiversity loss and a driver of several forms of degradation (Fig. 1). The integrity of the basin also depends on maintaining sufficient forest cover (*119*). Preventing additional degradation will also benefit from the conditions required to curb deforestation, such as the strengthening of land tenure, environment-oriented credit concession, and the provision of sustainable income and livelihood alternatives that can attenuate social inequalities (*124*).

But it is also clear that actions taken to prevent deforestation are not enough and must be supported by other interventions, such as preventing illegal logging (*34*), implementing large-scale investments and capacity building for a shift to fire-free cattle ranching, and supporting smallholders to reduce, eliminate, or better control the use of fires in agriculture. Initiatives to curb degradation (and stimulate restoration) arising from the private sector should be encouraged by public policies, learning from previous initiatives such as the efforts to avoid deforestation in the Amazonian soybean production sector (*125*, *126*). All these actions will benefit from improvements in the monitoring of tropical forest degradation. As spaceborne light-detecting and ranging (LiDAR) technology becomes increasingly cost-effective (*127*), the combination of its ability to detail canopy structure with optical imagery is a promising avenue for operationalizing the monitoring of disturbances linked to degradation (*128*). Other innovative ground-based monitoring initiatives such as the "smart forests" concept could be useful in contexts where disturbances such as timber extraction are key threats (an example is given by the Rainforest Connection initiative, https://rfcx.org/). Finally, efforts to reduce degradation will all be supported by rapid and multidisciplinary advances in our socioenvironmental understanding of tropical forest degradation that can provide a robust platform on which to co-construct appropriate policies and programs to curb it (*6*).

REFERENCES AND NOTES

1. Y. Malhi, T. A. Gardner, G. R. Goldsmith, M. R. Silman, P. Zelazowski, Tropical Forests in the Anthropocene. *Annu. Rev. Environ. Resour.* **39**, 125–159 (2014). doi: 10.1146/annurev-environ-030713-155141
2. X.-P. Song *et al*., Global land change from 1982 to 2016. *Nature* **560**, 639–643 (2018). doi: 10.1038/s41586-018-0411-9; pmid: 30089903
3. D. Nepstad *et al*., Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science* **344**, 1118–1123 (2014). doi: 10.1126/science.1248525; pmid: 24904156
4. A. S. L. Rodrigues *et al*., Boom-and-bust development patterns across the Amazon deforestation frontier. *Science* **324**, 1435–1437 (2009). doi: 10.1126/science.1174002; pmid: 19520958
5. H. J. Geist, E. F. Lambin, Proximate Causes and Underlying Driving Forces of Tropical Deforestation: Tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations. *Bioscience* **52**, 143–150 (2002). doi: 10.1641/0006-3568(2002)052[0143:PCAUDF]2.0.CO;2
6. C. H. L. Silva Junior *et al*., Amazonian forest degradation must be incorporated into the COP26 agenda. *Nat. Geosci.* **14**, 634–635 (2021). doi: 10.1038/s41561-021-00823-z
7. J. Barlow *et al*., Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. *Nature* **535**, 144–147 (2016). doi: 10.1038/nature18326; pmid: 27362236
8. L. V. Gatti *et al*., Amazonia as a carbon source linked to deforestation and climate change. *Nature* **595**, 388–393 (2021). doi: 10.1038/s41586-021-03629-6; pmid: 34262208
9. C. H. L. Silva Junior *et al*., Persistent collapse of biomass in Amazonian forest edges following deforestation leads to unaccounted carbon losses. *Sci. Adv.* **6**, eaaz8360 (2020). doi: 10.1126/sciadv.aaz8360; pmid: 32998890
10. L. E. O. C. Aragão *et al*., 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nat. Commun.* **9**, 536 (2018). doi: 10.1038/s41467-017-02771-y; pmid: 29440640
11. E. L. Bullock, C. E. Woodcock, C. Souza Jr., P. Olofsson, Satellite-based estimates reveal widespread forest degradation in the Amazon. *Glob. Chang. Biol.* **26**, 2956–2969 (2020). doi: 10.1111/gcb.15029; pmid: 32022338
12. E. A. T. Matricardi *et al*., Long-term forest degradation surpasses deforestation in the Brazilian Amazon. *Science* **369**, 1378–1382 (2020). doi: 10.1126/science.abb3021; pmid: 32913104
13. S. L. Maxwell *et al*., Degradation and forgone removals increase the carbon impact of intact forest loss by 626. *Sci. Adv.* **5**, eaax2546 (2019). doi: 10.1126/sciadv.aax2546; pmid: 31692892
14. Y. Qin *et al*., Carbon loss from forest degradation exceeds that from deforestation in the Brazilian Amazon. *Nat. Clim. Chang.* **11**, 442–448 (2021). doi: 10.1038/s41558-021-01026-5
15. A. Tyukavina *et al*., Types and rates of forest disturbance in Brazilian Legal Amazon, 2000-2013. *Sci. Adv.* **3**, e1601047 (2017). doi: 10.1126/sciadv.1601047; pmid: 28439536
16. W. S. Walker *et al*., The role of forest conversion, degradation, and disturbance in the carbon dynamics of Amazon indigenous territories and protected areas. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 3015–3025 (2020). doi: 10.1073/pnas.1913321117; pmid: 31988116
17. J. Barlow *et al*., The critical importance of considering fire in REDD+ programs. *Biol. Conserv.* **154**, 1–8 (2012). doi: 10.1016/j.biocon.2012.03.034
18. D. M. Lapola *et al*., Limiting the high impacts of Amazon forest dieback with no-regrets science and policy action. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 11671–11679. doi: 10.1073/pnas.1721770115
19. J. A. Parrotta *et al*., "Conclusions" in *Understanding relationships between biodiversity, carbon, forests and people: The key to achieving REDD+ objectives*, J. A. Parrotta, C. Wildburger, S. Mansourian, Eds. (IUFRO, Vienna, 2012), pp. 139–146.
20. L. Olsson *et al*., "Land Degradation" in *Climate Change and Land: An IPCCSpecial Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, P. R. Shukla *et al*., Eds. (2019), pp. 345–436; https://doi.org/10.1017/9781009157988.006.
21. J. Ghazoul, R. Chazdon, Degradation and Recovery in Changing Forest Landscapes: A Multiscale Conceptual Framework. *Annu. Rev. Environ. Resour.* **42**, 161–188 (2017). doi: 10.1146/annurev-environ-102016-060736
22. G. G. Ribeiro Neto *et al*., Attributing the 2015/2016 Amazon basin drought to anthropogenic influence. *Clim. Resil. Sustain.* **1**, e25 (2022). doi: 10.1002/cli2.25
23. E. Berenguer *et al*., Tracking the impacts of El Niño drought and fire in human-modified Amazonian forests. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2019377118 (2021). doi: 10.1073/pnas.2019377118; pmid: 34282005
24. S. L. Lewis, P. M. Brando, O. L. Phillips, G. M. F. van der Heijden, D. Nepstad, The 2010 Amazon drought. *Science* **331**, 554 (2011). doi: 10.1126/science.1200807; pmid: 21292971
25. K. Withey *et al*., Quantifying immediate carbon emissions from El Niño-mediated wildfires in humid tropical forests. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **373**, 20170312 (2018). doi: 10.1098/rstb.2017.0312; pmid: 30297469
26. W. F. Laurance *et al*., An Amazonian rainforest and its fragments as a laboratory of global change. *Biol. Rev. Camb. Philos. Soc.* **93**, 223–247 (2018). doi: 10.1111/brv.12343; pmid: 28560765
27. G. P. Asner *et al*., Selective logging in the Brazilian Amazon. *Science* **310**, 480–482 (2005). doi: 10.1126/science.1118051; pmid: 16239474
28. E. Rutishauser *et al*., Rapid tree carbon stock recovery in managed Amazonian forests. *Curr. Biol.* **25**, R787–R788 (2015). doi: 10.1016/j.cub.2015.07.034; pmid: 26394096
29. M. A. Cochrane *et al*., Positive feedbacks in the fire dynamic of closed canopy tropical forests. *Science* **284**, 1832–1835 (1999). doi: 10.1126/science.284.5421.1832; pmid: 10364555
30. D. V. Silverio *et al*., Fire, fragmentation, and windstorms: A recipe for tropical forest degradation. *J. Ecol.* **107**, 656–667 (2019). doi: 10.1111/1365-2745.13076
31. FAO, "Terms and definitions" in *Global Forest Resources Assessment*, FAO, Ed. (FAO, Rome, 2020), pp. 1–26.
32. J. Barlow, E. Berenguer, R. Carmenta, F. França, Clarifying Amazonia's burning crisis. *Glob. Chang. Biol.* **26**, 319–321 (2020). doi: 10.1111/gcb.14872; pmid: 31729092
33. P. B. Duffy, P. Brando, G. P. Asner, C. B. Field, Projections of future meteorological drought and wet periods in the Amazon. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 13172–13177 (2015). doi: 10.1073/pnas.1421010112; pmid: 26460046
34. P. H. S. Brancalion *et al*., Fake legal logging in the Brazilian Amazon. *Sci. Adv.* **4**, eaat1192 (2018). doi: 10.1126/sciadv.aat1192; pmid: 30116781
35. M. Longo *et al*., Impacts of degradation on water, energy, and carbon cycling of the Amazon tropical forests. *J. Geophys. Res. Biogeosci.* **125**, JG005677 (2020). doi: 10.1029/2020JG005677; pmid: 32999796
36. R. Ranasinghe *et al*., "Climate Change Information for Regional Impact and for Risk Assessment" in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, V. Masson-Delmotte *et al*., Eds. (Cambridge Univ. Press, 2021).
37. A. Baccini, W. Walker, L. Carvalho, M. Farina, R. A. Houghton, Response to Comment on "Tropical forests are a net carbon source based on aboveground measurements of gain and loss". *Science* **363**, eaat1205 (2019). doi: 10.1126/science.aat1205; pmid: 30630897
38. A. Baccini *et al*., Tropical forests are a net carbon source based on aboveground measurements of gain and loss. *Science* **358**, 230–234 (2017). doi: 10.1126/science.aam5962; pmid: 28971966
39. M. C. Hansen, P. Potapov, A. Tyukavina, Comment on "Tropical forests are a net carbon source based on aboveground measurements of gain and loss". *Science* **363**, eaar3629 (2019). doi: 10.1126/science.aar3629; pmid: 30630898
40. L. Giglio, L. Boschetti, D. P. Roy, M. L. Humber, C. O. Justice, The Collection 6 MODIS burned area mapping algorithm and product. *Remote Sens. Environ.* **217**, 72–85 (2018). doi: 10.1016/j.rse.2018.08.005; pmid: 30220740
41. G. C. Hurtt *et al*., Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6. *Geosci. Model Dev.* **13**, 5425–5464 (2020). doi: 10.5194/gmd-13-5425-2020
42. I. Harris, T. J. Osborn, P. Jones, D. Lister, Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Sci. Data* **7**, 109 (2020). doi: 10.1038/s41597-020-0453-3; pmid: 32246091
43. Materials and methods are available as supplementary materials.
44. P. M. Brando *et al*., The gathering firestorm in southern Amazonia. *Sci. Adv.* **6**, eaay1632 (2020). doi: 10.1126/sciadv.aay1632; pmid: 31950083
45. S. S. da Silva *et al*., Impact of fires on an open bamboo forest in years of extreme drought in southwestern Amazonia.

Reg. Environ. Change **20**, 127 (2020). doi: 10.1007/s10113-020-01707-5
46. S. Pueyo *et al*., Testing for criticality in ecosystem dynamics: The case of Amazonian rainforest and savanna fire. *Ecol. Lett.* **13**, 793–802 (2010). doi: 10.1111/j.1461-0248.2010.01497.x; pmid: 20528900
47. E. A. R. Carvalho Jr., E. N. Mendonça, A. Martins, T. Haugaasen, Effects of illegal logging on Amazonian medium and large-sized terrestrial vertebrates. *For. Ecol. Manage.* **466**, 118105 (2020). doi: 10.1016/j.foreco.2020.118105
48. PRODES-INPE, Satellite monitoring of the Amazon forest (2022), (available at http://www.obt.inpe.br/prodes).
49. A. Tyukavina *et al*., Aboveground carbon loss in natural and managed tropical forests from 2000 to 2012. *Environ. Res. Lett.* **10**, 074002 (2015). doi: 10.1088/1748-9326/10/7/074002
50. C. Piponiot *et al*., Carbon recovery dynamics following disturbance by selective logging in Amazonian forests. *eLife* **5**, e21394 (2016). doi: 10.7554/eLife.21394; pmid: 27993185
51. R. Walker *et al*., Modeling spatial decisions with graph theory: Logging roads and forest fragmentation in the Brazilian Amazon. *Ecol. Appl.* **23**, 239–254 (2013). doi: 10.1890/11-1800.1; pmid: 23495649
52. E. L. Bullock, C. E. Woodcock, Carbon loss and removal due to forest disturbance and regeneration in the Amazon. *Sci. Total Environ.* **764**, 142839 (2021). doi: 10.1016/j.scitotenv.2020.142839; pmid: 33131878
53. E. Berenguer *et al*., A large-scale field assessment of carbon stocks in human-modified tropical forests. *Glob. Chang. Biol.* **20**, 3713–3726 (2014). doi: 10.1111/gcb.12627; pmid: 24865818
54. A. Pontes-Lopes *et al*., Drought-driven wildfire impacts on structure and dynamics in a wet Central Amazonian forest. *Proc. Biol. Sci.* **288**, 20210094 (2021). doi: 10.1098/rspb.2021.0094; pmid: 34004131
55. C. V. J. Silva *et al*., Estimating the multi-decadal carbon deficit of burned Amazonian forests. *Environ. Res. Lett.* **15**, 114023 (2020). doi: 10.1088/1748-9326/abb62c
56. J. Barlow, C. A. Peres, B. O. Lagan, T. Haugaasen, Large tree mortality and the decline of forest biomass following Amazonian wildfires. *Ecol. Lett.* **6**, 6–8 (2003). doi: 10.1046/j.1461-0248.2003.00394.x
57. A. C. Staver *et al*., Thinner bark increases sensitivity of wetter Amazonian tropical forests to fire. *Ecol. Lett.* **23**, 99–106 (2020). doi: 10.1111/ele.13409; pmid: 31642170
58. O. L. Phillips, S. Rose, A. M. Mendoza, P. N. Vargas, Resilience of southwestern Amazon forests to anthropogenic edge effects. *Conserv. Biol.* **20**, 1698–1710 (2006).
59. O. L. Phillips *et al*., Drought sensitivity of the Amazon rainforest. *Science* **323**, 1344–1347 (2009). doi: 10.1126/science.1164033; pmid: 19265020
60. C. V. J. Silva *et al*., Drought-induced Amazonian wildfires instigate a decadal-scale disruption of forest carbon dynamics. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **373**, 20180043 (2018). doi: 10.1098/rstb.2018.0043; pmid: 30297477
61. D. Zuleta, A. Duque, D. Cardenas, H. C. Muller-Landau, S. J. Davies, Drought-induced mortality patterns and rapid biomass recovery in a terra firme forest in the Colombian Amazon. *Ecology* **98**, 2538–2546 (2017). doi: 10.1002/ecy.1950; pmid: 28719081
62. R. J. FletcherJr., Multiple edge effects and their implications in fragmented landscapes. *J. Anim. Ecol.* **74**, 342–352 (2005). doi: 10.1111/j.1365-2656.2005.00930.x
63. Brasil, "Quarta comunicação nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima" (Brasília, 2021).
64. A. Esquivel-Muelbert *et al*., Compositional response of Amazon forests to climate change. *Glob. Change Biol.* **25**, 39–56 (2019).
65. I. Numata, K. Khand, J. Kjaersgaard, M. A. Cochrane, S. S. Silva, Forest evapotranspiration dynamics over a fragmented forest landscape under drought in southwestern Amazonia. *Agric. For. Meteorol.* **306**, 108446 (2021). doi: 10.1016/j.agrformet.2021.108446
66. P. M. Brando *et al*., Droughts, Wildfires, and Forest Carbon Cycling: A Pantropical Synthesis. *Annu. Rev. Earth Planet. Sci.* **47**, 555–581 (2019). doi: 10.1146/annurev-earth-082517-010235
67. L. T. Smith, L. E. O. C. Aragão, C. E. Sabel, T. Nakaya, Drought impacts on children's respiratory health in the Brazilian Amazon. *Sci. Rep.* **4**, 3726 (2014). doi: 10.1038/srep03726; pmid: 24430803
68. N. de Magalhães, H. Evangelista, T. Condom, A. Rabatel, P. Ginot, Amazonian Biomass Burning Enhances Tropical Andean Glaciers Melting. *Sci. Rep.* **9**, 16914 (2019). doi: 10.1038/s41598-019-53284-1; pmid: 31780676
69. F. França, J. Barlow, B. Araújo, J. Louzada, Does selective logging stress tropical forest invertebrates? Using fat stores to examine sublethal responses in dung beetles. *Ecol. Evol.* **6**, 8526–8533 (2016). doi: 10.1002/ece3.2488; pmid: 28031804
70. A. C. Lees, C. A. Peres, Rapid avifaunal collapse along the Amazonian deforestation frontier. *Biol. Conserv.* **133**, 198–211 (2006). doi: 10.1016/j.biocon.2006.06.005
71. L. L. Jacob, B. S. Prudente, L. F. A. Montag, R. R. Silva, The effect of different logging regimes on the ecomorphological structure of stream fish assemblages in the Brazilian Amazon. *Hydrobiologia* **848**, 1027–1039 (2021). doi: 10.1007/s10750-020-04508-3
72. F. M. França *et al*., El Niño impacts on human-modified tropical forests: Consequences for dung beetle diversity and associated ecological processes. *Biotropica* **52**, 252–262 (2020). doi: 10.1111/btp.12756
73. V. Jirinec *et al*., Morphological consequences of climate change for resident birds in intact Amazonian rainforest. *Sci. Adv.* **7**, eabk1743 (2021). doi: 10.1126/sciadv.abk1743; pmid: 34767440
74. L. A. M. Mestre, M. A. Cochrane, J. Barlow, Long-term Changes in Bird Communities after Wildfires in the Central Brazilian Amazon. *Biotropica* **45**, 480–488 (2013). doi: 10.1111/btp.12026
75. L. G. Ziccardi, P. M. L. de Alencastro Graça, E. O. Figueiredo, P. M. Fearnside, Decline of large-diameter trees in a bamboo-dominated forest following anthropogenic disturbances in southwestern Amazonia. *Ann. For. Sci.* **76**, 110 (2019). doi: 10.1007/s13595-019-0901-4
76. C. J. Gardner, J. E. Bicknell, W. Baldwin-Cantello, M. J. Struebig, Z. G. Davies, Quantifying the impacts of defaunation on natural forest regeneration in a global meta-analysis. *Nat. Commun.* **10**, 4590 (2019). doi: 10.1038/s41467-019-12539-1; pmid: 31611554
77. J. Barlow, C. A. Peres, Effects of Single and Recurrent Wildfires on Fruit Production and Large Vertebrate Abundance in a Central Amazonian Forest. *Biodivers. Conserv.* **15**, 985–1012 (2006). doi: 10.1007/s10531-004-3952-1
78. L. N. Paolucci *et al*., Lowland tapirs facilitate seed dispersal in degraded Amazonian forests. *Biotropica* **51**, 245–252 (2019). doi: 10.1111/btp.12627
79. D. Vanham *et al*., Environmental footprint family to address local to planetary sustainability and deliver on the SDGs. *Sci. Total Environ.* **693**, 133642 (2019). doi: 10.1016/j.scitotenv.2019.133642; pmid: 31635013
80. J. Barlow *et al*., The future of hyperdiverse tropical ecosystems. *Nature* **559**, 517–526 (2018). doi: 10.1038/s41586-018-0301-1; pmid: 30046075
81. V. Galaz, B. Crona, A. Dauriach, B. Scholtens, W. Steffen, Finance and the Earth system – Exploring the links between financial actors and non-linear changes in the climate system. *Glob. Environ. Change* **53**, 296–302 (2018). doi: 10.1016/j.gloenvcha.2018.09.008
82. R. Rajão *et al*., The rotten apples of Brazil's agribusiness. *Science* **369**, 246–248 (2020). doi: 10.1126/science.aba6646; pmid: 32675358
83. A. T. Leite-Filho, B. S. Soares-Filho, J. L. Davis, G. M. Abrahão, J. Börner, Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. *Nat. Commun.* **12**, 2591 (2021). doi: 10.1038/s41467-021-22840-7; pmid: 33972530
84. M. G. Ceddia, U. Gunter, A. Corriveau-Bourque, Land tenure and agricultural expansion in Latin America: The role of Indigenous Peoples' and local communities' forest rights. *Glob. Environ. Change* **35**, 316–322 (2015). doi: 10.1016/j.gloenvcha.2015.09.010
85. M. Lentini, R. Palmieri, L. Sobral, "Atividade florestal madeireira no norte do Pará: do projeto Jari ao combate à ilegalidade e ao advento das concessões florestais" in *Florestas de Valor. Desenvolvimento territorial e sustentabilidade: a experiência do IMAFLORA no Norte do Pará*, R. Palmieri, Ed. (IMAFLORA, Belém, 2020), pp. 64–93.
86. C. Adams, R. S. S. Murrieta, R. A. Sanches, Agricultura e alimentação em populações ribeirinhas das várzeas do Amazonas: Novas perspectivas. *Ambiente Soc.* **8**, 65–86 (2005). doi: 10.1590/S1414-753X2005000100005
87. S. L. Francelino-Gonçalves-Dias, P. Mendonça, "Deforestation and Slave Labour in the Amazon: Contesting the sustainability of the cattle industry" in *7th International Critical Management Studies (CMS) Conference* (Naples, 2011).
88. R. D. Garrett *et al*., Explaining the persistence of low income and environmentally degrading land uses in the Brazilian Amazon. *Ecol. Soc.* **22**, art27 (2017). doi: 10.5751/ES-09364-220327
89. P. Shanley, M. da Serra Silva, T. Melo, R. Carmenta, R. Nasi, From conflict of use to multiple use: Forest management innovations by small holders in Amazonian logging frontiers. *For. Ecol. Manage.* **268**, 70–80 (2012). doi: 10.1016/j.foreco.2011.05.041
90. V. L. Camilotti, P. Pinho, E. S. Brondízio, M. I. S. Escada, The Importance of Forest Extractive Resources for Income Generation and Subsistence among Caboclos and Colonists in the Brazilian Amazon. *Hum. Ecol. Interdiscip. J.* **48**, 17–31 (2020). doi: 10.1007/s10745-020-00127-7
91. S. C. das C. Xavier *et al*., Lower Richness of Small Wild Mammal Species and Chagas Disease Risk. *PLOS Negl. Trop. Dis.* **6**, e1647 (2012).
92. F. Michalski, C. A. Peres, Disturbance-mediated mammal persistence and abundance-area relationships in Amazonian forest fragments. *Conserv. Biol.* **21**, 1626–1640 (2007). doi: 10.1111/j.1523-1739.2007.00797.x; pmid: 18173486
93. P. F. Pinho *et al*., Ecosystem protection and poverty alleviation in the tropics: Perspective from a historical evolution of policy-making in the Brazilian Amazon. *Ecosyst. Serv.* **8**, 97–109 (2014). doi: 10.1016/j.ecoser.2014.03.002
94. A. McGregor, S. Coulthard, L. Camfield, "Measuring what matters: the role of well-being methods in development policy and practice", ODI Development Progress (London, 2015), 20-p. Available at: https://cdn.odi.org/media/documents/9688.pdf.
95. A. Y. Vittor, G. Z. Laporta, M. A. M. Sallum, R. T. Walker, The COVID-19 crisis and Amazonia's indigenous people: Implications for conservation and global health. *World Dev.* **145**, 105533 (2021). doi: 10.1016/j.worlddev.2021.105533; pmid: 36570383
96. W. A. Campanharo, A. P. Lopes, L. O. Anderson, T. F. M. R. da Silva, L. E. O. C. Aragão, Translating Fire Impacts in Southwestern Amazonia into Economic Costs. *Remote Sens. (Basel)* **11**, 764 (2019). doi: 10.3390/rs11070764
97. M. O. Nawaz, D. K. Henze, Premature Deaths in Brazil Associated With Long-Term Exposure to $PM_{2.5}$ From Amazon Fires Between 2016 and 2019. *Geohealth* **4**, GH000268 (2020). doi: 10.1029/2020GH000268; pmid: 32864540
98. Human Rights Watch, "Rainforest mafias: How violence and impunity fuels deforestation in Brazil's Amazon," Human Rights Watch, New York (2019).
99. A. B. Chimeli, R. R. Soares, The Use of Violence in Illegal Markets: Evidence from Mahogany Trade in the Brazilian Amazon. *Am. Econ. J. Appl. Econ.* **9**, 30–57 (2017). doi: 10.1257/app.20160055
100. K. Whyte, Too late for indigenous climate justice: Ecological and relational tipping points. *Wiley Interdiscip. Rev. Clim. Change* **11**, e603 (2020). doi: 10.1002/wcc.603
101. R. Carmenta, E. Coudel, A. M. Steward, Forbidden fire: Does criminalising fire hinder conservation efforts in swidden landscapes of the Brazilian Amazon? *Geogr. J.* **185**, 23–37 (2019). doi: 10.1111/geoj.12255
102. P. Daszak *et al*., "Workshop Report on Biodiversity and Pandemics of the Intergovernmental Platform on Biodiversity and Ecosystem Services" (Bonn, 2020); https://doi.org/10.5281/zenodo.4147317.
103. J. H. Ellwanger *et al*., Beyond diversity loss and climate change: Impacts of Amazon deforestation on infectious diseases and public health. *An Acad Bras Cienc*. **92** (2020). doi: 10.1590/0001-3765202020191375
104. J. A. Foley *et al*., Amazonia revealed: Forest degradation and loss of ecosystem goods and services in the Amazon Basin. *Front. Ecol. Environ.* **5**, 25–32 (2007). doi: 10.1890/1540-9295(2007)5[25:ARFDAL]2.0.CO;2
105. A. P. D. Aguiar, G. Câmara, M. I. S. Escada, Spatial statistical analysis of land-use determinants in the Brazilian Amazonia: Exploring intra-regional heterogeneity. *Ecol. Modell.* **209**, 169–188 (2007). doi: 10.1016/j.ecolmodel.2007.06.019
106. D. M. Lapola *et al*., Impacts of climate change and the end of deforestation on land use in the Brazilian Legal Amazon. *Earth Interact.* **15**, 1–29 (2011). doi: 10.1175/2010EI333.1
107. W. F. Laurance *et al*., Environment. The future of the Brazilian Amazon. *Science* **291**, 438–439 (2001). doi: 10.1126/science.291.5503.438; pmid: 11228139
108. B. S. Soares-Filho *et al*., Modelling conservation in the Amazon basin. *Nature* **440**, 520–523 (2006). doi: 10.1038/nature04389; pmid: 16554817

109. Y. Le Page *et al*., Synergy between land use and climate change increases future fire risk in Amazon forests. *Earth Syst. Dyn.* **8**, 1237–1246 (2017). doi: 10.5194/esd-8-1237-2017
110. D. Armenteras, U. Murcia, T. M. González, O. J. Barón, J. E. Arias, Scenarios of land use and land cover change for NW Amazonia: Impact on forest intactness. *Glob. Ecol. Conserv.* **17**, e00567 (2019). doi: 10.1016/j.gecco.2019.e00567
111. B. L. De Faria *et al*., Current and future patterns of fire-induced forest degradation in Amazonia. *Environ. Res. Lett.* **12**, 095005 (2017). doi: 10.1088/1748-9326/aa69ce
112. T. O. Assis, A. P. D. Aguiar, C. von Randow, C. A. Nobre, Projections of future forest degradation and CO_2 emissions for the Brazilian Amazon. *Sci. Adv.* **8**, eabj3309 (2022). doi: 10.1126/sciadv.abj3309; pmid: 35704589
113. A. P. D. Aguiar *et al*., Land use change emission scenarios: Anticipating a forest transition process in the Brazilian Amazon. *Glob. Chang. Biol.* **22**, 1821–1840 (2016). doi: 10.1111/gcb.13134; pmid: 26511401
114. R. B. de Andrade *et al*., Scenarios in tropical forest degradation: Carbon stock trajectories for REDD. *Carbon Balance Manag.* **12**, 6 (2017). doi: 10.1186/s13021-017-0074-0; pmid: 28413850
115. L. E. O. C. Aragão, Y. E. Shimabukuro, The incidence of fire in Amazonian forests with implications for REDD. *Science* **328**, 1275–1278 (2010). doi: 10.1126/science.1186925; pmid: 20522775
116. P. Delacote, A. Angelsen, Reducing Deforestation and Forest Degradation: Leakage or Synergy? *Land Econ.* **91**, 501–515 (2015). doi: 10.3368/le.91.3.501
117. S. N. Panfil, C. A. Harvey, REDD+ and Biodiversity Conservation: A Review of the Biodiversity Goals, Monitoring Methods, and Impacts of 80 REDD+ Projects. *Conserv. Lett.* **9**, 143–150 (2016). doi: 10.1111/conl.12188
118. M. G. Fonseca *et al*., Effects of climate and land-use change scenarios on fire probability during the 21st century in the Brazilian Amazon. *Glob. Chang. Biol.* **25**, 2931–2946 (2019). doi: 10.1111/gcb.14709; pmid: 31304669
119. T. E. Lovejoy, C. Nobre, Amazon Tipping Point. *Sci. Adv.* **4**, eaat2340 (2018). doi: 10.1126/sciadv.aat2340; pmid: 29492460
120. U. Pascual *et al*., Governing for Transformative Change across the Biodiversity–Climate–Society Nexus. *Bioscience* **72**, 684–704 (2022). doi: 10.1093/biosci/biac031
121. J. Reed, J. Van Vianen, E. L. Deakin, J. Barlow, T. Sunderland, Integrated landscape approaches to managing social and environmental issues in the tropics: Learning from the past to guide the future. *Glob. Chang. Biol.* **22**, 2540–2554 (2016). doi: 10.1111/gcb.13284; pmid: 26990574
122. M. Skutsch, E. Turnhout, REDD+: If communities are the solution, what is the problem? *World Dev.* **130**, 104942 (2020). doi: 10.1016/j.worlddev.2020.104942
123. C. Streck, REDD+ and leakage: Debunking myths and promoting integrated solutions. *Clim. Policy* **21**, 843–852 (2021). doi: 10.1080/14693062.2021.1920363
124. R. DeFries *et al*., Improved household living standards can restore dry tropical forests. *Biotropica* **54**, 1480–1490 (2022). doi: 10.1111/btp.12978; pmid: 36582545
125. H. K. Gibbs *et al*., Brazil's Soy Moratorium. *Science* **347**, 377–378 (2015). doi: 10.1126/science.aaa0181; pmid: 25613879
126. D. F. Amaral, J. B. de Souza Ferreira Filho, A. L. S. Chagas, M. Adami, Expansion of soybean farming into deforested areas in the amazon biome: The role and impact of the soy moratorium. *Sustain. Sci.* **16**, 1295–1312 (2021). doi: 10.1007/s11625-021-00942-x
127. S. Hancock, C. McGrath, C. Lowe, I. Davenport, I. Woodhouse, Requirements for a global lidar system: Spaceborne lidar with wall-to-wall coverage. *R. Soc. Open Sci.* **8**, 211166 (2021). doi: 10.1098/rsos.211166; pmid: 34877004
128. S. Francini, G. D'Amico, E. Vangi, C. Borghi, G. Chirici, Integrating GEDI and Landsat: Spaceborne Lidar and Four Decades of Optical Imagery for the Analysis of Forest Disturbances and Biomass Changes in Italy. *Sensors* **22**, 2015 (2022). doi: 10.3390/s22052015; pmid: 35271161
129. C. M. Souza Jr. *et al*., Reconstructing three decades of land use and land cover changes in Brazilian biomes with Landsat archive and Earth Engine. *Remote Sens.* **12** (2020). doi: 10.3390/rs12172735
130. S. Saatchi *et al*., Persistent effects of a severe drought on Amazonian forest canopy. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 565–570 (2013). doi: 10.1073/pnas.1204651110; pmid: 23267086

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Tables S1 and S2

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