Analytical Review

The drivers and impacts of Amazon forest degradation

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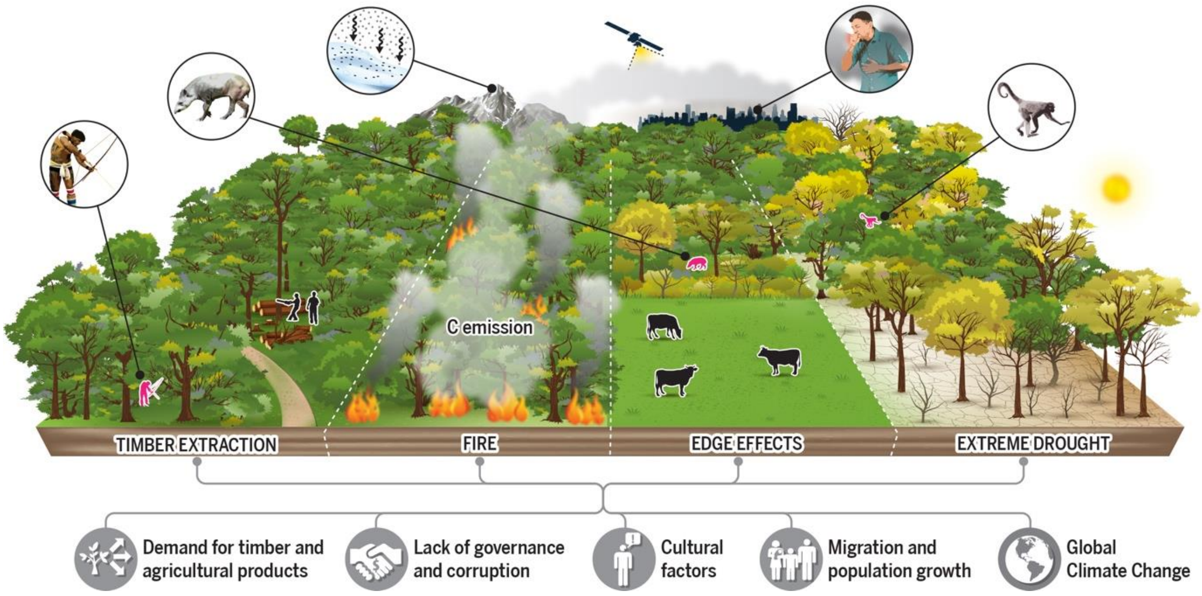
Extended summary

BACKGROUND: Most analyses of land-use/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. Amongst 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 $x10^6$ 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 $x10^6$ km^2, or 38% of the remaining Amazonian forests. Estimated carbon loss from these forest disturbances ranges from 0.05 to 0.20 PgC yr^{-1} and is comparable to carbon loss from deforestation (0.06-0.21 PgC yr^{-1}). Disturbances can bring about as much biodiversity loss as deforestation itself, while 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, while 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 the four main disturbances will remain a major threat and source of carbon fluxes to the atmosphere, independent of deforestation trajectories.

OUTLOOK: While some disturbances can be tackled by curbing deforestation, others 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 multi-disciplinary advances in our socio-environmental understanding of tropical forest degradation, providing a robust platform on which to co-construct appropriate policies and programs to curb it.



(Extended Summary Figure) 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 impacting forest-dweller livelihoods, or remote, for example with smoke affecting people's health in cities or causing the melting of Andean glaciers due to black carbon deposition. Credit: Alex Argozino/Studio Argozino.

Abstract

Approximately 2.5 $x10^6$ km^2 of the Amazon forest is 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 0.2 PgC yr^{-1}, which is equivalent to, if not greater than, the emissions from Amazon deforestation (0.06-0.21 PgC yr^{-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/land-cover change 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 appear to disproportionately impact 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 separate process from deforestation is thus critical for improving observation networks, climate change and conservation policies, and models on the resilience of the Amazon forest and its human populations, in light of ongoing land-cover/use changes and increased frequency of climate extremes.

In this Analytical 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 significant 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 timescale) 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 (*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, non-timber forest product extraction, and defaunation could all alter forest condition. However, the four disturbances we focus on can all be studied across the Amazon 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*). In contrast, while 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, like 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 due to 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.

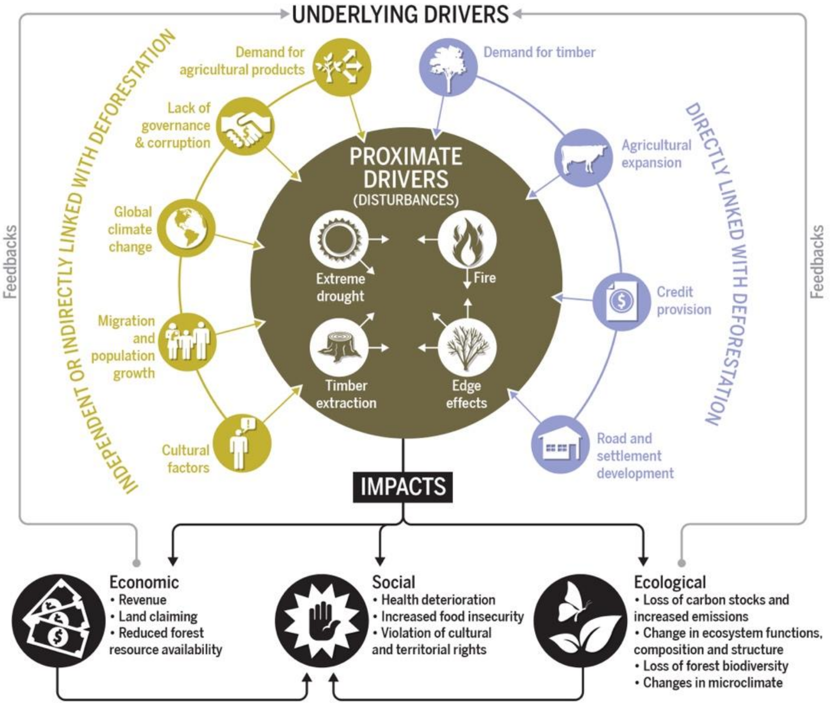


Fig. 1. **A conceptual model of the drivers, impacts and feedbacks of Amazon forest degradation.** Some of the underlying drivers of disturbance (outer edge of the circle) are also directly related to deforestation processes (purple), while others are not (yellow). The four main disturbances leading 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 feedback 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). Credit: Alex Argozino/Studio Argozino.

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 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 multi-scale 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).

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 (*37*) (see Section "Spatial extent and severity").

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 Section "Underlying drivers of disturbance"). 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 Section "Social and economic dimensions").

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*, *38*–*40*). The only existing pan-Amazonian direct estimate using a Landsat time series (*11*) indicates an area of 1,036,800 ± 24,800 km^2 impacted by human and natural disturbances between 1995 and 2017 (47,127 ± 1,127 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 (*41*), timber extraction (*42*), edge effects (*9*), and drought (*43*). 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)(*44*).

Forest fires intensify during drought years (*10*, *23*, *24*, *45*, *46*) leading to acute peaks in burned area: 14,584 km^2 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 (7,701 km^2). While the extent of Amazonian fires during recent droughts has already been large, much larger mega-fires are also possible (*47*). 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 (*42*) shows an annual rate of 6,623.5 km^2 y^{-1} affected by timber extraction from 2001-2018 in the Brazilian Amazon. The first Brazilian Amazon-wide study estimated a rate of 11,537 km^2 y^{-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 4,479 km^2 y^{-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 employed here — which is based on national census statistics — and a remotely-sensed approach. Estimates suggest that approximately 50% (or even more) of the timber extraction in the Amazon is illegal (*48*), meaning that this does not appear in either the national census or in 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*, *49*, *50*), 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 provides 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 systematic 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 (*51*), and the extraction of timber is often associated with edges (*52*). Not all the extreme droughts observed in the Amazon in the analyzed 2001-2018 period have been unequivocally attributed to human-induced climate change (*22*). That said, 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 largely determined by the types of disturbances considered (with much larger area estimates if less-severe disturbances, like droughts, are included; Fig. 2), the spatial and temporal ranges of the studies, and their distinct methods (*16*, *38–40*, *53*). 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*).

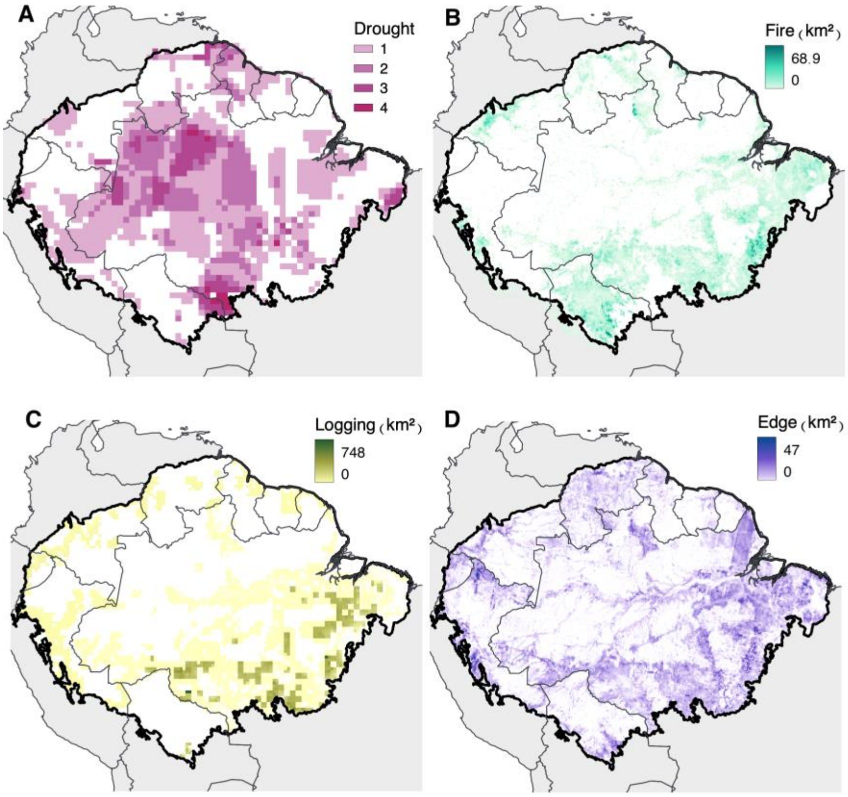


Fig. 2. **Current (2001-2018) spatial distribution of the four main drivers of forest degradation in the Amazon forest**, excluding deforestation and savanna areas. **(A)** Extreme drought occurrence, **(B)** burned area, **(C)** timber extraction, **(D)** area within a forest edge. The datasets employed (*23*, *41–43*, *130*), processing steps and numerical estimates are shown in the Supplementary Material.

Ecological impacts

Changes in carbon stocks and basin-wide emissions

Disturbance type and intensity are strong predictors of the magnitude of change in above-ground carbon stocks (i.e., severity; Box 1). Carbon losses are often greatest in burned forests, compared to the other disturbances (*54*). 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*, *55*, *56*) (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*, *57*). Smaller effects have been recorded in drier Amazonian regions (*45*) where trees are protected by thicker bark (*58*) and in less-seasonal regions where fire intensity may be limited by high fuel moisture content (*55*). 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 four 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 (*59*). Finally, extreme droughts bring about short-term carbon losses of 1% to 8% (*23*, *60*) (Fig. 3).

Time since disturbance is an important determinant of above-ground carbon stocks. When forests are burned, the recovery of carbon stocks from tree recruitment and growth is offset by high rates of ongoing tree mortality (*23*, *57*, *61*), such that burned forest can be a net source of carbon emissions for up to 7 years after the fire, and hold c. 25% less carbon after 30 years (*46*, *56*, *61*). Biomass recovery times after logging are almost directly proportional to the volume of timber extracted, such that extraction of 10, 25 or 50% of pre-logging 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 (*51*). Carbon losses from edge effects are most pronounced after the first four 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 (*62*) and sustained effects lasting at least three 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 (*54*), and edge effects are greater when forests are exposed to multiple edges (*63*). 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 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 PgC yr^{-1} for a different combination of disturbances (*10–16*), which are comparable to deforestation emission estimates of 0.06 to 0.21 PgC yr^{-1} (*50*, *64*). 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*).

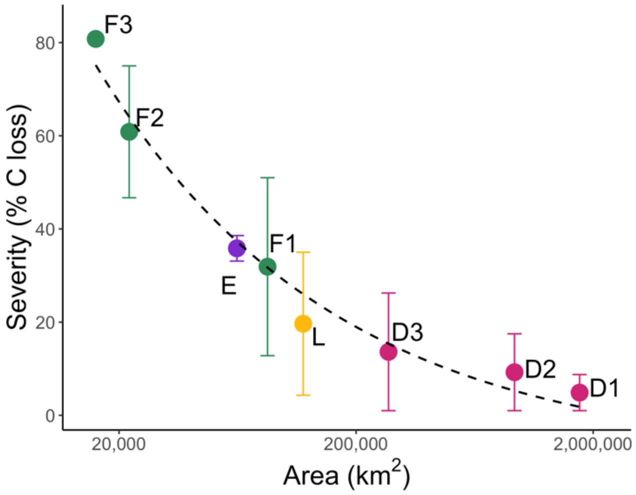


Fig. 3. The relationship among the area affected between 2001 and 2018 and disturbance severity (carbon loss). D: extreme drought; E: edge effects; F: forest fire; L: timber extraction (logging). Numbers denote single events (1) or repeated fires or droughts (2 or 3). Area is shown on a $\log_{10}$ scale.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

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*, *51*). Reductions in forest biomass and changes in species composition also affect water cycling (*65*). Forest edges generate 5% less evapotranspiration (ET) than forest interiors (*66*), and degraded forests provide between 2% to 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*, *67*), with recovery occurring within seven years of repeated forest fires (*67*). Amazonian fires also reduce air quality many thousands of kilometers from the source (*68*), while soot deposits are accelerating glacier melt in the Andes (*69*).

Biodiversity and ecosystem functioning

Fires, timber extraction and edge effects reduce the number of forest species (*7*, *70*) and species with the highest conservation values (*7*). In landscapes with c. 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 (*71*). The impacts of forest disturbance extend to aquatic biota, and even reduced-impact logging affects the composition and functional traits of stream fishes (*72*). Disturbance also disrupts multi-trophic processes such as pollination, decomposition, seed dispersal and herbivory (*73*), and drives sub-lethal changes in the morphology or physiology of birds (*74*) and dung beetles (*70*).

The post-disturbance 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 (*75*). Recovery can be further impeded where forests have been affected by previous disturbances (*73*), or where succession is dominated by lianas, palms, bamboos or invasive grasses (*46*, *76*). Finally, fauna can support post-disturbance forest recovery, with birds, terrestrial ungulates and primates all helping disperse seeds (*77*). Some of these taxa are resilient to low-intensity disturbance (*78*) and contribute to forest regeneration where hunting is controlled and there is connectivity with undisturbed forests (*79*).

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 associated with the underlying drivers of 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, and investment banks contributing to geopolitical and market forces (*80*). These actors are impacted by the outcomes of disturbances (e.g., smoke from fires), and the resulting degraded 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) are misaligned. Benefits often accrue to external stakeholders while 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 (*81*, *82*). For example, a small fraction of (large-scale) landholders account for most forest loss (*83*), contributing to degradation via edge-creation through deforestation, escaped pasture renewal fires (*32*), reduced regional rainfall (*8*), and ultimately contributing to global climate change itself via carbon emissions (*84*). Forest loss is strongly associated with commodity production with material benefits accruing to wealthy regional and international actors (*85*). For instance, even omitting the sizable clandestine market (*34*, *48*), timber extraction in the Brazilian Amazon generated US$459.5 million in 2018 (*86*), 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) (*87*) (Fig. 4A). Other benefits accruing locally include income from hired labor in logging camps (*88*). However, these economic benefits tend to be short term (*4*), poorly negotiated, disproportionately small, and do not compensate for the local damages that forest degradation inflicts (*89*, *90*).

Multi-dimensional burdens exacerbate the vulnerabilities of marginalized groups

Forest degradation creates burdens to multi-dimensional human well-being which 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 (*91*). Timber extraction reduces the availability of species that contribute to nutritional diversity or provide oils or medicines (*90*, *91*). Reductions in diversity of host species undermines the 'dilution effect' (where low-quality host abundance buffers parasite dispersal), increasing vector-borne diseases (e.g., Chagas disease) (*92*). The dense understory of fire-affected forests makes hunting harder (mobility in Fig. 4B) and reduce availability of preferred game species (*93*). Forest degradation can impact fish abundance in streams, rivers and floodplains, with implications for the nutritional diversity and food security of local communities (*72*). 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 (*89*), compounding existing vulnerabilities associated with structural marginalization (*94*).

Although less well understood than material impacts, burdens related to forest degradation also affect the relational and subjective dimensions of people's lives, which make important contributions to human well-being (*95*). 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) (*96*). Public-health burdens accrue from the smoke associated with fires and include premature deaths and school closures (*68*, *97*, *98*), potentially reducing the learning lifetime of local children (public education in Fig. 4B). Incidence of violence rises when land conflicts associated with forest degradation occur (*99*), and within temporary settlements created for logging operations (*100*).

The loss of forest resources following degradation can negatively influence relational dimensions of people's lives, including social-cultural reproduction, cohesion and cultural practices. For example, forest degradation can erode communal sites, impair place attachments, impact interactions with the forest and ways of knowing and of using its resources. Degradation can also heighten perceptions of vulnerability and risk due to place dislocation, transformation, and threat of potential resettlement (*101*).

Diffuse and indirect burdens accrue to external actors

Amazon forest degradation also burdens 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 (*84*). Fires can influence the sustainability of water availability in distant (e.g., Andean) cities, with the deposition of black carbon accelerating glacial melt (*69*). Fire also causes material damage to the timber sector affecting commercially unexplored forests (*17*, *102*), and other losses to potential revenue and to the region's economy (e.g., through airport closures) (*97*).

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 (*103*, *104*). Further, the relationship between ecosystem degradation and regional public health has the potential to be important (*105*). Estimates suggest that the loss of ecosystem services due to 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 significant intangible relational and quality-of-life impacts. Better understanding of the multi-faceted suite of burdens extending from degradation across scales could help to inform appropriate policy responses and galvanize support in society for a shift towards more sustainable use of the forest.

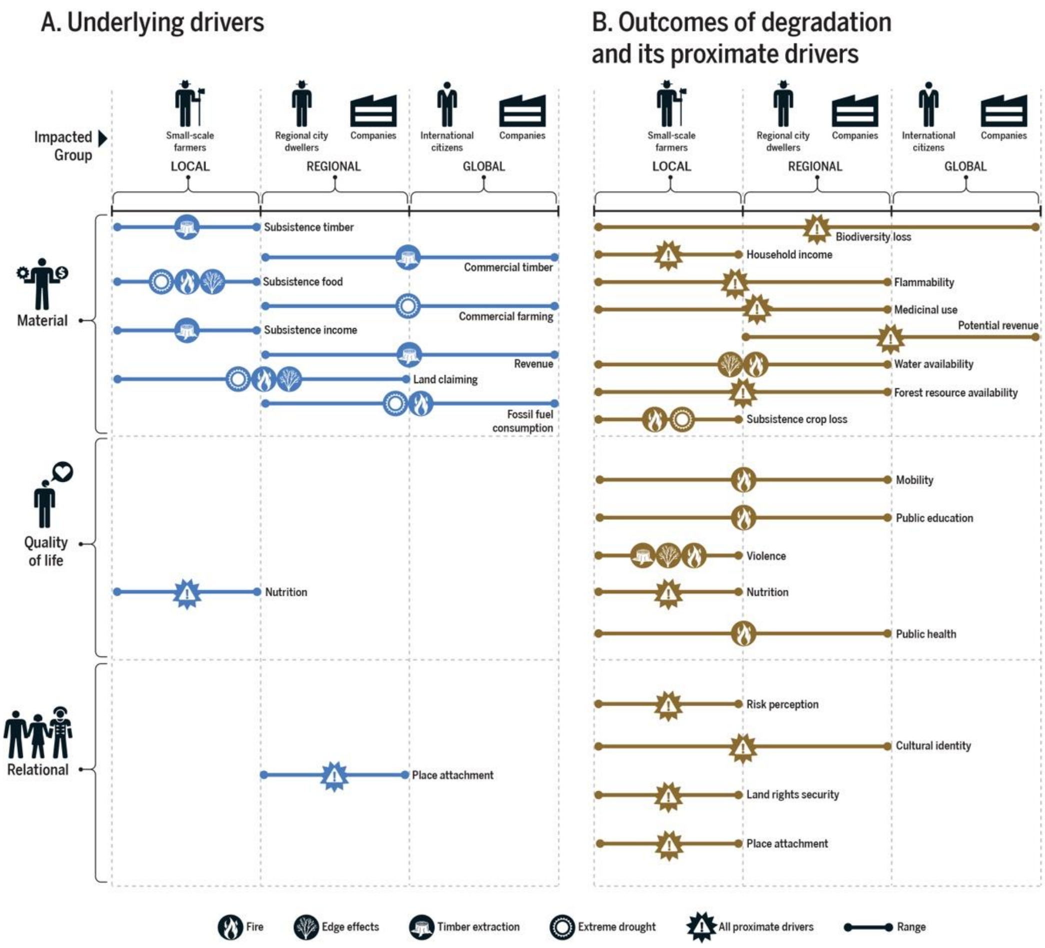


Fig. 4. Socioeconomic benefits and burdens of Amazon forest degradation and its drivers are unevenly distributed. **(A)** The underlying drivers of disturbance generate mainly material benefits, while **(B)** the resulting forest degradation generates burdens that are unevenly distributed among stakeholders 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. Disturbance type is indicated by the icon and the range of impacts by the horizontal extent. Credit: Alex Argozino/Studio Argozino.

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*, *106*–*109*). Only five studies have projected future Amazon forest degradation in a spatially-explicit way, either covering the entire Amazon biome (*110*) or focusing on the Colombian (*111*), Brazilian (*112*, *113*) or southern Brazilian Amazon (*45*). Modeling approaches include mechanistic (*112*), statistical (*111*, *113*) and hybrid (*45*, *110*) methods. Studies assessing the proximate causes (Fig. 2) focused on fire occurrence driven by deforestation and climate change (*45*, *110*), fire intensity driven by climate change (*112*), edge effects due to forest fragmentation (*111*), or mixed causes (*113*). Two further studies modelled degradation in a non-spatially explicit way using fixed degradation-to-deforestation ratios (*114*) or statistical relationships of carbon loss caused by logging and fire (*115*). 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 (*110*), (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 (*110*)], (iii) climate change can boost fire intensity and ignition sources promoting fire-driven degradation (*112*), (iv) roads promote degradation as well as deforestation (*52*), and that (v) carbon dioxide emissions from degradation can overwhelm those from deforestation (*45*, *111*), and the carbon uptake from regeneration (*114*).

Combining previously published projections of the individual main disturbances that cause degradation (*44*), 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 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 PgC yr^{-1} in the GOV scenario and 0.42 PgC yr^{-1} in the BAU scenario, this upper limit being considerably higher than the upper limit of 0.2 PgC yr^{-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 (*113*). In fact, 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 (*116*). However, our assessment also indicates the importance of designing and implementing intervention strategies that address degradation and deforestation as distinct processes (*117*, *118*).

Emissions in the GOV scenario are dominated by fire (59%), followed by droughts (38%) and logging (3%). However, in the BAU scenario, under RCP8.5 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; Table S2).

While 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 section Underlying drivers of disturbance). 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 (*119*)(*120*).

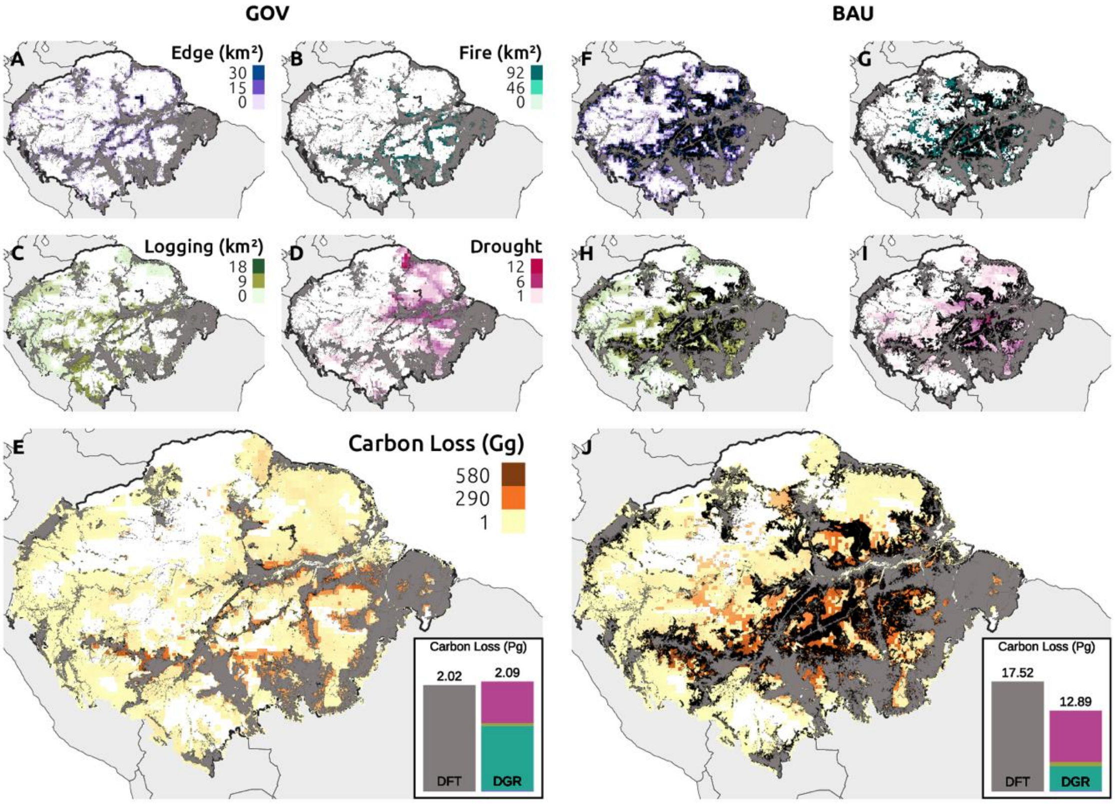


Fig. 5. First-order 2050 projections of Amazon forest degradation through its main drivers. Projections of 2019-2050 changes in the main proximate drivers of Amazon forest degradation. (**A** and **F**) edge effects (*109*); (**B** and **G**) fire occurrence (*112*); (**C** and **H**) timber extraction (*42*); (**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 (*44*, *109*). 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 material for methods and numerical results.

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., towards 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*, *83*). 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 (*121*, *122*).

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 (*118*), and the identification of key actors and drivers in REDD+ projects is confusing, even when those address the well-known process of deforestation (*123*). Moreover, while 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 (*124*), 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, considering the integrity of the basin depends on it maintaining sufficient forest cover (*120*). 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 (*125*).

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 the efforts to avoid deforestation in the Amazonian soybean production sector (*126*, *127*). All these actions will benefit from improvements in the monitoring of tropical forest degradation. As spaceborne LiDAR technology becomes increasingly cost-effective (*128*), 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 (*129*). 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 multi-disciplinary advances in our socio-environmental understanding of tropical forest degradation that can provide a robust platform on which to co-construct appropriate policies and programs to curb it (*6*).

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Authors contributions

DML, PP, JB, LEOCA, EB, RC, HML, HS, CS and CHLS were responsible for the conceptualization of this review, data visualization and analysis, and writing of the original draft. HML and DML acquired funding that made this study possible. All other authors contributed additional ideas and revised subsequent drafts.

Competing interests

The authors declare no competing interests.

Data and materials availability

All previously published data shown here can be obtained through the references cited in Supplementary Material and Methods (*44*). The codes and data resulting from the analyses of such previously published material are freely available at https://doi.org/10.25824/redu/EGJAYI.

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Supplementary Materials for

Analytical Review
The drivers and impacts of Amazon forest degradation
Lapola et al. 2022
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This file includes:

Materials and Methods
Tables S1 and S2

Materials and Methods

Data

The reference forested area for the 2001-2018 period is the forest extent from Mapbiomas collection 2 in 2018 with 81.3% accuracy (*130*), and all quantified degradation refers to remaining forests in the year 2018. The 2001-2018 degradation caused by extreme drought was obtained from processing CRU 4.0 datasets for precipitation and evapotranspiration at 0.5° resolution (*43*). The CRU temperature and precipitation datasets have correlations of 0.38 and 0.56, respectively with their cross-validation data.

The fire degradation extent in the 2001-2018 period was obtained by combining the forest extent in 2018 with the annual burned area from MCD64A1 at 500-m resolution (*41*). The quality of the burned area product (MCD64A1) has been assessed previously in other studies, and local validations in the Amazon showed a suitable performance for this product.

Timber extraction extent was obtained from the Land-Use Harmonization 2 (LUH2) dataset, which gives the percent of logged area within the grid cell based on national census statistics (*42*). This dataset was used in the analysis shown in Fig. 2 (and also in the projections shown in Fig. 5). The only modification made was to transform the original fraction of the grid that was logged to the absolute logged area. We did not provide information on the frequency of timber extraction, given that the LUH2 (the only Amazon-wide dataset) does not supply recurrence data.

To quantify the extent of forests under edge effect in the 2001-2018 period, we used the approach proposed by Silva-Junior et al. (*9*), using the Mapbiomas forest area (*130*).

Mean values on the relation between disturbance extent and degradation severity (Fig. 3) were calculated based on minimum and maximum severity values found in the literature: once-burned forests (*55*, *57*); twice-burned forests (*17*, *29*); thrice-burned forests (*29*, *54*); edge [(*6*) for all values]; selective logging [(*28*) for both minimum and maximum values]; drought (*23*, *60*): in the absence of information on the impacts of repeated drought, we simply used cumulative values from individual events, assuming that, due to forest recovery, the minimum value could remain constant even in the event of multiple droughts, while the maximum value could double in the case of a total absence of post-drought recovery.

The 2050 projections on disturbances and carbon emissions (Fig. 5) were elaborated using existing projections of the main drivers of Amazon forest degradation and deterministic factors to derive carbon-loss estimates. The deforestation projection scenarios were created with the adaptation of the output data from the model SimAmazonia 1 (*109*), which uses socioeconomic and environmental variables to create spatially explicit deforestation projections from 2002 to 2050 (we used SimAmazonia 1's 2019-2050 annual deforestation maps). To calculate carbon loss, we used the condition prior to the degradation established by using an aboveground biomass dataset for the year 2000, provided by the Global Forest Watch (GFW).

For the forest edge effects projection, the calculation of carbon losses followed the method proposed by Silva-Junior et al. (*9*), extrapolating measurements from airborne LiDAR (Light Detection And Ranging). We determined the border between forest and anthropogenic land cover by using the data from the deforestation projections (*109*), using a grid with resolution of 960 m.

To assess the 2019-2050 degradation caused by droughts, we used the CMIP5 projections (RCP4.5 for the GOV scenario and RCP8.5 for the BAU scenario), to calculate the respective maximum cumulative water deficit (MCWD) of each year for each pixel.

The 2019-2050 area of timber extraction was obtained from the Land-Use Harmonization 2 (LUH2) dataset (*42*).

The effect of fire on 2019-2050 degradation of the Amazon forest was estimated using projections from a dynamic carbon model that accounts for forest flammability, fire behavior and fire effects (*112*). These projections were used to estimate the carbon loss in the forests remaining after projected deforestation (*109*). They also assumed the RCP4.5 climate for the GOV scenario and the RCP8.5 climate for the BAU scenario.

Analyses

The cumulative extent of degradation drivers was quantified between 2001 and 2018 by combining each degradation driver grid with the reference forest. In regard to extreme droughts, we calculated the maximum cumulative water deficit (MCWD) pixel-by-pixel within forested areas following (*116*) but considering the climatic year instead of the calendar year. We used the dry season start and length maps from (*23*) to establish the climatic year for each pixel. We then calculated the anomaly annually by obtaining the shift from the mean (in standard deviations) for each pixel. We considered the pixels in which the MCWD anomaly values fell below minus two standard deviations as areas under extreme drought degradation. The extent of drought degradation and the frequency of recurrence were obtained from the annual cumulative occurrence maps.

Burned area was aggregated annually and accumulated over the years to calculate the extent of single and repeated fire events.

Edge effects area in the 2001-2018 period was estimated by reclassifying the MapBiomas maps (*130*) to binary maps; for the original class "Forest Formation," we assigned the value "1" (forest) and for the other classes, the value "0" (non-forest). In addition, we removed from all binary forest cover maps all secondary forests (*9*) that grew between 1986 and 2018. To map the forest edges, we adopted 120-m depth as proposed by Silva-Junior et al. (*9*) within the 2000-2018 period. For all forest pixels we calculated the Euclidean distance from the boundary formed by the contact of forest and non-forest pixels. We then classified the resulting distance pixels into the following classes: non-forest (equal to 0 m), forest interior (greater than 120 m) and forest-edge (between 30 and 120 m). However, the forest edges for the year 2000 were used to remove the natural edges (e.g., the borders between forest and water) from the other maps.

The total overlapping area for the 2001-2018 period was obtained at the pixel level by overlaying the four layers, considering all the possible combination of overlaps between drivers. We used the layers with their original pixel size and did not consider the fraction applied to the timber extraction layer, because the exact location of the timber extraction and where there is overlap with other drivers. The proportion of all overlapping area relative to total degraded area (without corrections) was then multiplied by the total degraded area with corrections (e.g. considering timber extraction fraction and forest area within the drought layer).

We created a reference raster file in the South America Albers Equal-Area Conic projection (ESRI:102033) with a resolution of 9600m to combine different data sets to produce the 2050 projection of degradation. All the spatial data used were reprojected based on the reference raster. The use of an equal-area projection allowed us to maintain pixel alignment when aggregating and disaggregating pixels and also avoided creating borders with variable sizes depending on the latitude.

In our analysis, the governance deforestation scenario (GOV) assumes a halting of illegal deforestation in 2030, after which legal deforestation continues (10% of the expected total deforestation each year) that is gradually reduced to zero by 2050. The business-as-usual scenario (BAU) assumes the same trajectory as the original BAU deforestation projections (*109*). These deforestation projections were used as the spatial base (mask) for the calculations of the degradation by all of the four main disturbance types.

After the classification of the edges, we summed up all the raster layers to obtain the age of the edges from SimAmazonia 1 projections (*109*). The edge ages were used to estimate the carbon loss as the explanatory variable in a nonlinear hyperbolic regression: $Closs = (-42.815(\pm 2.966) \times Eage) / (0.836(\pm 0.411) + Eage)$. After calculating the percentage of carbon loss for each pixel classified as an edge, we calculated the actual carbon loss by multiplying the biomass map by the carbon loss factor and an area factor of 0.028 (the mean edge fraction estimated for a pixel of 960 m. The factor was obtained by aggregating the results of the original study (*9*) in a grid with 960-m resolution; the results were then averaged to obtain the factor.

In regard to 2019-2050 degradation caused by droughts, we classified the pixels with the most extreme drought values (MCWD values larger than 2 times the standard deviation) as the ones where a severe drought occurred in a given year. The classified pixels were then summed to represent the recurrence of droughts in each pixel from 2019 to 2050. To calculate the carbon loss due to degradation caused by extreme droughts, we used deterministic factors that relate carbon loss to droughts (*23, 60*) ranging from 0.01 to 0.08.

The 2019-2050 estimated timber extraction percentage that fell within protected areas was not taken into account. We only calculated carbon loss caused by future timber extraction in pixels with remaining forests according to the deforestation projections (*109*). Timber extraction projections considered the RCP4.5 climate in the GOV scenario and the RCP8.5 climate in the BAU scenario. Our estimate of carbon loss from timber extraction used deterministic factors found in the literature, ranging from 0.0428 to 0.35 in the GOV and BAU scenarios.

Supplementary tables

Table S1. Supporting table for Figure 2. Current (2001-2018) extent of the four main disturbances related to degradation in the Amazon forest. The extent of fire, edge effects, timber extraction, and extreme drought disturbances includes potential spatial overlapping with each other. As such estimates are provided on the extent of all possible overlapping between fire, edge effects and timber extraction disturbances, as well as every possible overlapping between all four drivers (see "Quantification of overlapping area" in Supplementary Material – Material and Methods). Final estimate of total degraded area (considering or not degradation caused by extreme drought) is obtained after summing up the area subject to the pertinent disturbances and subtracting the proper potential overlapping. Because of that operation the area and percentage value of each separate disturbance compared to the total degraded area can be greater than the final total degraded area, as is the case for extreme drought.

Variable	km^2	% of degraded area	% of Amazonian forest
Fire	122,624	4.8	1.8
Edge effects	188,531	7.4	2.8
Timber extraction	119,700	4.7	1.8
Extreme drought	2,740,647	107.8	41.1
Every overlap between any among fire, edge & timber	66,107	2.6	1.0
Every overlap btw. any of the 4 disturbances	628,909	24.7	9.4
Degraded forest area (discounting overlap) due fire, edge & timber	364,748	14.3	5.5
Degraded forest area (discounting overlap) due to all 4 disturbances	2,542,593	100.0	38.1
Total remaining Amazon forest area in 2018	6,673,908	-	100.0

Table S2. Supporting table for Figure 5. Projections on the future (2050) extent of the four main disturbances related to degradation in the Amazon forest and deforestation according to two scenarios, and associated carbon emissions. The extent of fire, edge effects, timber extraction, and extreme drought disturbances includes potential spatial overlapping with each other. As such estimates are provided on the extent of all possible overlapping between fire, edge effects and timber extraction disturbances, as well as every possible overlapping between all four drivers. Overlapping is calculated considering the data's original pixel size and considered the fraction applied to the timber extraction layer. See Supplementary Material – Material and Methods for methods used to produce Figure 5 and this table.

	Governance			**Business-as-usual**		
Variable	**Area (km^2)**	**Area (% of total remaining forest in 2050)**	**C emissions (PgC)**	**Area (km^2)**	**Area (% of total remaining forest in 2050)**	**C emissions (PgC)**
Fire	550,787	11.7	1.23	630,072	19.3	3.87
Edge effects	3,829	0.1	0.02	22,492	0.7	0.15
Timber extraction	60,429	1.3	0.06	114,629	3.5	0.69
Extreme drought	2,120,230	45.1	0.78	2,062,630	63.3	8.18
Every overlap btw. any of the 4 disturbances	328,666	7.0	0.29	460,326	14.1	2.50
Degraded forest (discounting overlap) due to all 4 disturbances	2,406,609	51.2	2.09	2,369,497	72.8	12.89
Deforestation in the 2019-2050 period	154,781	-	2.01	1,391,816	-	17.52
Total remaining Amazon forest area in 2050	4,696,681	100.0	-	3,256,392	100.0	-