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Measuring forest degradation via ecological-integrity indicators at multiple spatial scales

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ABSTRACT

Forests harbor some 80 % of Earth's terrestrial biodiversity and play a crucial role in sequestering and storing carbon that is linked to their ecological integrity and biological diversity functions. Forest degradation—the loss of forest-ecosystem integrity measured by changes to native-species composition, functional processes, and keystone structures—is a major source of emissions and significant cause of biodiversity decline. Addressing this loss is critically important for fulfilling the Paris Climate Agreement and the Kunming-Montreal Global Biodiversity Framework. Additionally, the United Nations (2021a) Strategic Plan for Forests 2017–2030 calls for a halt to both deforestation and degradation by 2030. However, many countries, particularly in the Global North, fail to fully acknowledge forest degradation as a problem within their own borders, and countries are not presently on track to meet the 2030 deadline. Building from established literature, we propose a principle, criteria, indicator and verifier (PCIV) approach that would enable monitoring of degradation at various scales, ranging from the loss of large, old trees to intact landscapes relative to reference conditions derived from primary, mature, historic, and semi-natural conditions. Degradation drivers include multiple forms of commercial logging and road building that alters native species composition, structure, and functionality. Case studies from three major forested biomes (temperate, boreal, and tropical) illustrate the geographic extent and types of degradation. We highlight an urgent call for countries to better detect and assess the cumulative damages of forest-degradation and to end it as promised.

1. Introduction

UN Secretary General António Guterres issued a planetary "red alert" in 2021 in response to the alarming findings of the IPCC 6th assessment (IPCC, 2021) that time is running out on avoiding calamitous losses to nature and people from unprecedented global overheating and humanity's expansive ecological footprint (IPBES, 2019). Integrated solutions involving emissions reductions across all sectors, combined with natural climate solutions are essential for addressing this mounting crisis (IPCC, 2021). Forests are the largest terrestrial carbon sinks and

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stocks on the planet (Pan et al., 2011; IUCN, 2021) and contain ~80 % of all terrestrial species (United Nations, 2023a). Additionally, forests with the highest ecological integrity are considered to be in the most stable state, even as they are naturally dynamic, because they lack anthropogenic disturbances (Funk et al., 2019).

Primary forests, which have the highest integrity and stability, are undisturbed by industrial uses, have functional processes, including the range of successional stages, and support characteristic native species (Kormos et al., 2017; Rogers et al., 2022). The large, old trees in these forests store disproportionate amounts of aboveground carbon (Stephenson et al., 2014), while the old-growth forest stage generally is among the most carbon dense ecosystems on the planet (Keith et al., 2009). Old-growth forests, in particular, may also function as important wildfire refugia (Lesmeister et al., 2021; DellaSala et al., 2022) and climate refugia (Wolf et al., 2021). However, only ~27 % of the planet's total forest cover remains in primary forest condition (FAO, 2020) and some countries (Europe, contiguous USA) are nearly devoid of the old-growth forest stage.

Given the critical ecosystem services that forests, particularly primary forests, provide, deforestation (permanent loss of forest cover) has been an ongoing focus of international forest policy since at least the United Nations Conference on Environment and Development in 1992. Importantly, from 2002 to 2023, deforestation of tropical rainforests increased at an alarming pace of 76.3 M ha (Global Forest Watch, 2024). However, deforestation is not the only threat to forests. Although estimates of global degradation are lacking, there is ample evidence that degradation is exerting major pressures on forests. For example, the United Nations Food and Agriculture Organization (2009) estimated that there were 800 M ha of degraded forests in the tropics alone. Haddad et al. (2015) reported that some 20 % to 70 % of forests globally were within 100-m and 1-km of a forest edge, respectively. Ibisch et al. (2016) found that while 80 % of the planet was roadless, these areas, which include many forest types, were fragmented into ~600,000 patches, more than half of which were < 1 km^2, and only 7 % of which were > 100 km^2. The most extreme impacts to biodiversity occur in heavily degraded areas (>68 % biomass removed) (Ewers et al., 2024). Additionally, the recent State of the World's Forests report (FAO, 2024) found that nearly 75 % of the world's total land area, particularly forests, rangelands and wetlands, had been degraded and transformed, and those losses would likely increase to >90 % within 30 years. Degraded forests are at a much higher risk of emitting carbon and reaching tipping points that increase with climate change effects, such as severe drought and wildfire, compared to forests undisturbed by industrial impacts (Lindenmayer et al., 2011).

Ending forest degradation has been a multilateral policy issue since the formation of the United Nations Forum on Forests in 2000. It was noted as a priority in the United Nations Forest Instrument (United Nations, 2007), and in the Global Forest Goals and Targets of the UN Strategic Plan for Forests 2030 (United Nations, 2015). At the United Nations (2021b) Climate Change Conference, 145 nations signed the Glasgow Leaders' Declaration on Forests and Land Use ("Glasgow Leaders' Declaration"), which seeks to "facilitate the alignment of financial flows with international goals to reverse forest loss and degradation" by 2030 and commits signatories to halting and reversing deforestation and land degradation by 2030. The Kunming-Montreal Global Biodiversity Framework (Convention on Biological Diversity, 2022) proposed 23 action-oriented global targets, including ensuring that at least 30 % of lands and waters are protected and degraded areas are under effective restoration by 2030. In addition, Goal A of this framework emphasized the need to ensure that "integrity, connectivity and resilience of all ecosystems are maintained, enhanced, or restored, substantially increasing the area of natural ecosystems by 2050." Target 1 of this framework also seeks "to bring the loss of areas of high biodiversity importance, including ecosystems of high ecological integrity, close to zero by 2030."

In December 2023, at the COP 28, 193 countries signed a decision under the United Nations Framework Convention on Climate Change (UNFCCC) on the outcome of the first global stocktake, emphasizing the importance of "enhanced efforts to halt and reverse deforestation and forest degradation by 2030" to meet global climate targets (UNFCCC, 2023), as well as the need for synergistic climate and biodiversity actions. This decision reflects the growing calls for integrated solutions since the Conferences of the Parties (COP) 25 and that escalating biodiversity loss and greenhouse gas emissions are intertwined, existential threats to humanity. Following the UNFCCC's decisions at COP 28, the Declaration of the High-Level Segment of the 19th session of the United Nations Forum on Forests (2024) also reaffirmed the United Nations (2021a) Strategic Plan for Forests, issuing a call for halting and reversing forest degradation.

At the regional level, policymakers in the European Union, for instance, have advanced marketplace standards limiting trade in commodities tied to deforestation and forest degradation (European Union, 2023), and major investors and companies have been integrating degradation avoidance efforts into their wood purchasing policies (e.g., Kimberly-Clark, 2018). Despite all this attention, not a single country is on track to meet the timeline of halting and reversing deforestation and degradation by 2030 (Forest Declaration Assessment, 2024). Degradation also has financial consequences as such losses have an estimated USD 4.3 trillion–20.2 trillion cost, affecting 3.2 billion people (Gibbs and Salmon, 2014; FAO, 2024).

2. Forest degradation tracking limitations

Tracking forest degradation is complicated by differences in definitions (Ghazoul et al., 2015) and methodologies (Betts et al., 2024). The Food and Agriculture Organization (FAO, 2020) introduced national reporting on in its Forest Resource Assessment. However, because only 58 governments representing 38 % of the world's forests responded, and methodologies and indicators varied greatly, results were deemed inconclusive. Notably, most responses came from tropical countries. Those that responded reported on degradation to the FAO (via Global Forest Resources Assessments) were based on a range of indicators, including the presence of forest disturbances (e.g., logging, wildfire); changes in forest structure (e.g., decreases in forest canopy); loss of productivity; loss of biodiversity; soil damage/erosion; reductions in the provision of ecosystem goods and services; negative effects on other land uses (e.g., by causing a loss of downstream water quality); loss of carbon, biomass, and growing stock. The UNFCCC also lacks a definition of forest degradation, and further compounded the issue with its adoption of forest carbon accounting rules that allow nations to utilize accounting methods that represent logging as carbon neutral, ignoring the significant reduction in carbon stock compared to unlogged forests, and failing to report on the loss of ecosystem integrity (Krug, 2018, Funk et al., 2019, Rogers et al., 2022, Mackey et al., 2022). Further, the utility of the United Nations (2023b) Sustainable Development Goal 15 in addressing forest degradation is limited by its focus solely on forest extent and not on indicators of forest ecosystem integrity.

While Betts et al. (2024) offered important insights into tracking degradation, their approach was based on net accounting whereby the loss of forest attributes at any given location could be "offset" by theoretical gains in another area over time. However, we argue that loss of high integrity forests cannot be offset. The ecosystem benefits that these forests, particularly primary forests and the old-growth stage provide, which includes long-term carbon accumulation and biodiversity maintenance, are so great that recovery times far exceed time frames for addressing the climate and biodiversity crises, and at worst they may be altogether irrecoverable (Gatti et al., 2015; Putz and Thompson, 2020). For instance, Bourgoin et al. (2024) concluded that the full recovery of forest structure after deforestation or degradation would require a centennial timescale. Importantly, Gasser et al. (2022) simulated forest degradation for Amazonia based on three scenarios: (1) End Gross Forest Loss; (2) End Net Forest Loss; and (3) End Tree Cover Loss (forest cover remains constant regardless of age class distributions). They concluded that the End Gross Forest Loss produced the greatest ecosystem benefits and the most meaningful compliance with halting and reversing forest loss and degradation by 2030. We agree that forest degradation should be assessed in terms of gross losses rather than a net accounting system.

Our objective is to provide a comprehensive framework to assess forest degradation based on tracking losses to ecosystem integrity as imposed by anthropogenic disturbances, ranging from the removal of individual large, old trees to stand and landscape alterations. Our approach differs from other studies that focus on large-scale ecological footprint analyses (Thompson et al., 2013; Potapov et al., 2017) and forest landscape integrity based largely on tree cover loss and connectivity (Grantham et al., 2020). Here, we compare anthropogenic impacts across scales to specific attributes in reference areas that have the highest ecosystem integrity for any given forest type.

3. Ecological integrity vs forest degradation

We define ecological integrity as a measure of the composition, structure, and function of an ecosystem in relation to the system's natural range of variation. This integrity concept integrates different characteristics of an ecosystem that collectively describe its ability to achieve and maintain its optimum operating state in the face of the prevailing environmental drivers and anthropogenic stressors, while continuing to maintain its self-organization and regeneration capacity (Mackey et al., 2024). We adopted the approach of Rogers et al. (2022) in identifying foundational elements for ecosystem integrity that include representative structures, processes, native species, and resilience. Additionally, ecosystem condition (the relative level of ecosystem integrity) can be based on the state, processes, and changes in the ecosystem, including: (1) carbon and nutrient stocks, (2) abiotic physical and chemical states such as water quantity and quality; (3) biotic composition, structure, and function; and (4) landscape diversity and connectivity (Rogers et al., 2022). In our approach, a forest with native species composition, keystone structures (e.g., biological legacies: large, old trees, snags, down wood, native understories), and functional processes (e.g., natural disturbances, food web complexities, pollinators, below ground processes, soil integrity) has high integrity compared to one where anthropogenic disturbance have destabilized these key elements in various degrees. Conversely, we refer to degradation as anthropogenic disturbances that trigger the immediate and long-term deterioration of integrity (Rogers et al., 2022; Mackey et al., 2024).

4. Reference conditions

Where they exist, the reference condition against which loss of ecological integrity will be measured is a primary or old-growth forest. However, in places lacking such forests, the reference can be derived from an historical determination of key features of a natural forest, mature forests in advanced post-disturbance successional stages, and naturally regenerating forests that are structurally complex (i.e., complex early seral, Swanson et al., 2010).

The integrity of primary and, where those no longer exist, near-natural forests, is due, in part, to their resistance to natural disturbances as a result of stable microhabitats within forest interiors, presence of large trees that can buffer fires and floods, and functional redundancy of species assemblages. High integrity forests are also resilient to natural disturbances via their ability to return to optimal operating conditions after a state-altering perturbation via natural successional pathways. Resilience in this case allows for succession to proceed in a circular fashion (i.e., "circular succession") from pioneering stage immediately after stand-replacing disturbance to old growth stage and back again when disturbed again and is a component of ecosystem integrity. Resilient properties of forests may include "seed rain" and germination after stand-replacing natural disturbances, epicormic branching, and biological legacies (e.g., dead trees, surviving shrubs and seed-dispersing animals) that lifeboat forests through successional stages (Swanson et al., 2010).

Importantly, we disagree with the FAO (2022) and the USDA Forest Service (2024) that natural processes such as insect outbreaks and wildfires are a form of degradation (i.e., a "threat" to ecosystems). Rather, many forest ecosystems are uniquely adapted to natural disturbances operating within historic bounds and require them to maintain integrity (Swanson et al., 2010). However, we acknowledge that this is complicated by the expanding impacts of climate change amplified by land use stressors that are shifting ecosystem dynamics in novel ways (IPCC, 2021).

We also consider forest management for commodity production to be a potential driver of degradation. While some (sensu Puettmann et al., 2015) exclude forest management from degradation considerations, we argue that it is indeed the case because compared to primary, old growth, and near-natural forests, logging, including under notional sustainable forest management regimes, typically results in highly skewed forest age classes toward young stages (stand and landscape), a loss of key components of structural complexity (Thorn et al., 2020), depleted carbon stocks (Malcolm et al., 2020), loss of biodiversity (including contributing to or driving decline of threatened or endangered species; Stewart et al., 2020), and/or reduced resistance and resilience to disturbances (DellaSala et al., 2022). Indeed, many legal, regulated forestry practices have a high risk of driving degradation.

5. Assessing degradation using a conceptualized framework

Anthropogenic impacts can accumulate spatially and temporally across a continuum of tree, stand, and landscape integrity losses that can be generally scored based on a broad suite of relative factors (Fig. 1, Table 1). In developing an evaluation framework, we drew upon a principle, criteria, indicator and verifier (PCIV) approach that is commonly used in the ecological literature (e.g., Gatica-Saavedra et al., 2017, Lemke et al., 2017, Schick et al., 2019, Soubry et al., 2021) and applied it in the context of ecological integrity changes (as in Mackey et al., 2023, 2024) (Table 1).

While degradation is represented as a continuum of ecosystem integrity loss, there are thresholds where ecosystems can flip to a fundamentally altered state that represent a substantially degraded landscape condition approaching deforestation (Fig. 1) (Lindenmayer et al., 2011). In juxtaposed situations, deforestation from one area may also interact with degradation of another via edge penetrance into the remaining fragment (Fig. 2).

Our framework can provide greater consistency and transparency in tracking degradation at multiple scales for government reporting, while helping to guide market-based solutions involving wood product supply chains that seek to avoid degradation (e.g., Kimberly-Clark, 2018). Moreover, ongoing monitoring of forest conditions using our framework can reveal where and when a degraded forest has partially or entirely recovered through natural or assisted ecological restoration. An example

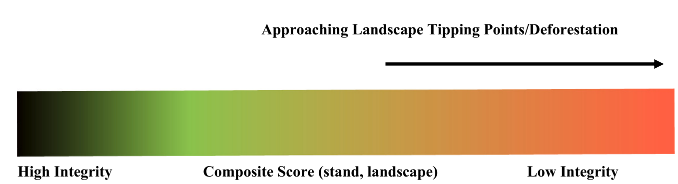


Fig. 1. Ecosystem integrity composite factors based on principles, criteria, indicators, and verifiers, as adapted from Mackey et al., 2024 and displayed in Table 1. Each of the factors in Table 1 can receive a scoring based on comparisons to reference conditions and site or regionally specific literature on those conditions relative to altered areas. For instance, many regions have information on road densities that impact hydrology and aquatic species and carbon stocks.

Table 1
Generalized framework for tracking forest degradation, building on the PCIV (principle, criteria, indicator, and verifier) ecosystem integrity approach (Mackey et al., 2023, 2024). The actual verifiers used in any given integrity assessment will vary depending on the availability of data and costs. For example, the Floristic Quality Assessment (Spyreas, 2019) requires detailed floristic knowledge, and the delineation of “young” from “mature” and “old growth” forest can be based on cutoffs in the reference forest condition. Some verifiers may overlap with others elsewhere in the table.

Principle	Criteria	Indicators	Verifiers
Ecosystem integrity	Structural quality	Vegetation structure	Basal area or tree density by young, mature, old stages (e.g., floristic quality assessment) Large snags, coarse woody debris Carbon stock levels (Mg/ha) all pools and by age classes Tree heights, canopy layering, biomass
	Ecosystem processes	Natural disturbances	Degree of altered fire and other disturbance regimes
		Nutrient cycling	Coarse woody Soil compaction Soil productivity Mycorrhizae functionality
		Optimal hydro-ecology	Unlogged watersheds Road-stream intersections Water quality limited streams Surface runoff Evapotranspiration rates
	Ecological composition	Ecosystem stability	Carbon stock (Mg/ha, all pools) average and range relative to reference Exotic vs native species (ratio)
		Adaptive potential	Potential genetic adaptations (e.g., natural resistance to pests), site factors (e.g., biological legacies following disturbance) Rare, threatened, at-risk species (e.g., IUCN Redlist, USA endangered species), focal species determinations Plant and animal richness Micro and macrorefugia (e.g., cool temperature, high moisture related to biophysical factors from within sites to landscape position)
	Ecosystem functionality (e.g., see Freudenberger et al., 2012)	Ecosystem complexity	Vegetation density, topographical heterogeneity, carbon storage, species richness of vascular plants, tree height, plant functional richness
		Climate buffering	Temperature remote-sensed data of forest patches (e.g., see Mann et al., 2023)
	Landscape characteristics	Spatial extent	High conservation value forests (e.g., https://www.hcvnetwork.org/hcv-approach; accessed December 11, 2024) Forest seral stages, especially old growth Patch sizes and distributions, especially large ones (total roadless area) Gamma diversity
		Spatial configuration	Barriers to wildlife movements Road density, mean/median roadless areas size (e.g., Ibisch et al., 2016) Intra-patch connectivity/fragmentation
		Temporal extent	Degree of cumulative impacts from roads, logging, other disturbances

is the northeastern forests of the United States that are reaching maturation (100+ years), recovering from expansive logging over a century ago. Mature (semi-natural) forests are approaching the reference or historical condition in this situation. Restoration can therefore simply focus on proforestation; the practice of allowing forests to become old-growth overtime (Moomaw et al., 2019). It can also include active measures that remove anthropogenic stressors like roads, livestock grazing, invasive species, and the reintroduction of extirpated species, all of which would drive the evaluation scores for degradation effects down over time.

6. Hypothetical application of the degradation framework

A hypothetical example is provided to illustrate how the PCIV scorings (Table 2) can work in a focal (managed) forest of interest being impacted by logging using a “spiderweb” diagram of scoring factors (Fig. 3) that compares focal areas to reference conditions such as primary and near-natural forests. This scoring of the framework can be conducted in any forest type and region and with enough replicates would be scalable to larger areas.

7. Regional examples of forest degradation in relation to the PCIV

We provide regional examples to illustrate the utility of the degradation framework in relation to Table 1 PCIV generally; however, the examples are not meant as a specific test of the approach. We recognize that subsequent studies are needed to apply the framework via statistically robust comparisons of focal sites with reference areas.

7.1. Degradation of tropical rainforest

Sustainable Forest Management (SFM) is a broad and somewhat imprecise term promoted globally since the United Nations Conference on Environment and Sustainable Development in Rio of 1992. The SFM concept is meant to guide the maintenance of a forest's ecological values while generating a sustained yield of timber (Putz and Thompson, 2020). In the tropics, SFM involves selective logging of large trees from a relatively small suite of commercially valued species that proports to be based on reduced-impact logging and post-logging silvicultural treatments to encourage regeneration (Putz and Thompson, 2020). However, a number of ecological factors in tropical forests conspire against truly ecologically sustainable practices. First, logging focuses on primary forests, where large old trees with a high volume of timber can still be found (Table 1: structural quality-vegetation structure). However, many of the exploited trees are important for wildlife, especially host-specific pollinators, and are important for long-term carbon storage and nutrient cycling (Table 1: nutrient cycling, soil compaction/productivity, ecological composition, ecosystem processes, ecosystem stability-carbon) (Zimmerman and Kormos, 2011).

Importantly, large trees generally represent a small percentage of the

Fig. 2. Deforestation on the border of Kayapo's territory, Pará, Brazil, showing stark contrast with a primary forest. Notably, edge penetrance from deforestation will creep into the juxtaposed primary forest causing spillover effects that trigger degradation in the primary forest as well (photo credits: Simone Giovine).

Table 2
Hypothetical degradation scoring factors for 4 variables in comparison to reference conditions. Scorings of 1 to 3 represent high to low integrity. Highest total scorings reflect highest degradation levels. Any and all of the PCIV in Table 1 can be included in this analysis.

	Above-ground biomass	Presence of key species	Old growth (%)	Lack of invasives	Forest degradation score
Reference forest	1	1	1	1	4
Focal forest A	2	3	2	2	9
Focal forest B	3	2	3	3	11

forest's total trees (<5 %), yet store up to 50 % of the above ground carbon (Stephenson et al., 2014; Fauset et al., 2015; Lutz et al., 2018). As a result, logged tropical forests store ~35 % less carbon than primary forests, and this amount decreases with successive logging operations (Mackey et al., 2020). Most tropical forests are also very sensitive to having their canopies opened up because that brings in secondary forest species that displace primary species, an invasion of vines and lianas, and an increase in fire proneness (Zimmerman and Kormos, 2011, Gatti et al., 2015) (Table 1: native species vs. invasive species, natural disturbance processes). Tropical forest logging therefore can have cascading effects on integrity especially when it scales up cumulatively across large landscapes (Table 1: landscape characteristics). Putz and Thompson (2020) found that the stocks of carbon and biodiversity in large primary tropical rainforests exceeded those in forests subjected to uses other than forest protection. Furthermore, because large trees tend to be slow-growing hardwood species, they require >100 years to recover from logging, if they recover at all (Mackey et al., 2020; Putz and Thompson, 2020), illustrating problems with adaptive potential and ecosystem stability (Table 1).

Even if logging intensity is lowered in tropical forests by removing only a small volume of timber, extending timber rotations, and following extensive pre- and post-logging best practices, it is typically not commercially viable (Zimmerman and Kormos, 2011, Romero et al., 2024, Putz and Thompson, 2020, Vidal et al., 2020). This is why operations often fell trees illegally, exceeding their allowable cuts, and often clear-felling is used to go after the high-value, large trees (Zimmerman and Kormos, 2011, Vidal et al., 2020).

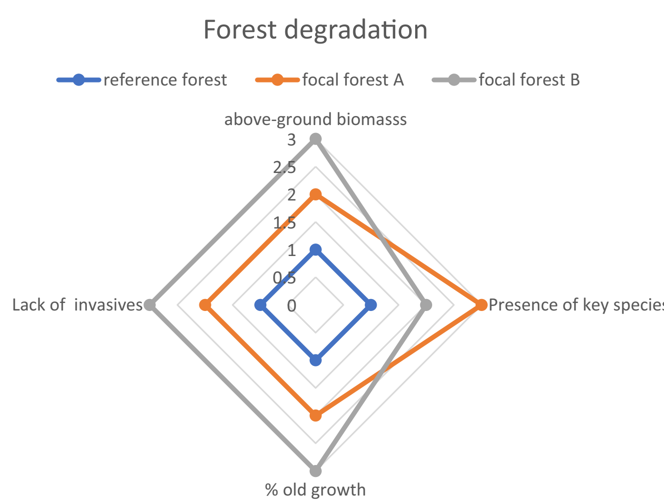


Fig. 3. Spiderweb schematic illustrating how the departure in integrity between two focal forests and a hypothetical reference condition can be scored (i.e., in comparison to primary forests, near-natural forest). The higher the overall score, the more significant the forest degradation. Statistical analyses can be applied to illustrate the main factors involved in degradation that best separate degraded sites from the reference condition.

7.2. *Degradation of dry fire-adapted forests of western United States*

Many "fire risk reduction" and "restoration" projects include substantial and frequent biomass removals (DellaSala et al., 2022), often targeting large trees and resulting in soil compaction and excessive understory impacts that can type-convert dense forests to open woodlands lacking native understories (Table 1: vegetation structure, nutrient cycling, soils, invasives) (Fig. 4). Impacts can accumulate across spatial scales (Table 1: landscape characteristics), affecting large areas logged and excessively burned in dry pine (*Pinus* spp.) and mixed-conifer forests, for example (Fig. 5a–c). Altered stands are then exposed to understory drying and over ventilation of forest canopies that can elevate fire spread rates and cause blow down of remaining trees (Table 1: ecosystem processes - natural disturbance). Tree mortality from removals and understory damage can also exceed that of fire disturbances (Hanson, 2022) (Table 1: ecosystem stability and adaptive potential). Moreover, excessive understory removals through mastication of shrubs and pile burning of slash can disrupt natural successional pathways with reverberating multi-functional ecosystem impacts (Ding and Eldridge, 2024), including the spread of invasive species within burn piles and soil damages (Table 1: invasive species, ecosystem processes, nutrient cycling-soils). Encroachment of woody plants, for instance, is likely to increase in many dry forest systems due to climatic shifts amplified by removal of understory plant species that may have synergistic relationships with tree establishment (Ding and Eldridge, 2024).

7.3. Degradation of boreal and temperate forests, Canada

Decades of extensive clearcut logging has led to diverse and multi-faceted forest degradation that illustrates removal of important old forest structures with scalable impacts (Table 1: vegetation structure and landscape characteristics) (Fig. 6a, b). This includes: (1) habitat loss and fragmentation caused by roads and other linear features that are driving substantial declines of boreal caribou (*Rangifer tarandus caribou*; Stewart et al., 2020) (Table 1: spatial configuration - road density, ecological composition - rare, threatened, at-risk species); (2) changes in tree composition (Table 1: ecological composition-tree species composition) that have led to declines in dozens of bird species in the east coast Acadia forests - even where the amount of tree cover has remained relatively stable (Betts et al., 2022) (Table 1: adaptive potential-plant/animal richness); (3) loss of coarse woody debris and reduced nutrient cycling (Table 1: ecosystem processes-nutrient cycling); (4) declines of focal species like American marten (*Martes americana*), which is also important to many northern Indigenous peoples (Farnell et al., 2020) (Table 1: adaptive potential); (5) cumulative logging and road building that have increased extreme flooding in British Columbia's coastal and inland temperate rainforests (Pham and Alilal, 2024) (Table 1: ecosystem processes-hydrology); and (5) conversion of carbon-rich, primary forests to planted forests that decrease landscape-level carbon storage (Table 1: vegetation structure-carbon stock levels) (Malcolm et al., 2020; Mackey et al., 2024). Such impacts accumulate spatially and temporally (Table 1: landscape characteristics-spatial and temporal).

7.4. Degradation of tall wet forests of Victoria, Australia

Although native forest logging has officially ceased in the tall wet forests of the Australian State of Victoria, various active management practices within these forests continue to degrade them.

First, so-called "firebreaks" spanning 1450-km are fragmenting tall, wet forests and cool temperate rainforests (Department of Energy, Environment and Climate Action (DECCA), 2024) (Table 1: landscape characteristics-spatial extent, configuration) even within the Yarra Ranges National Park in the Central Highlands (Fig. 7). Removing large (>1.2-m diameter, 200–350+ years old) trees is impacting the nesting and denning habitat of the Southern Greater Glider (*Petauroides volans*), recently uplisted to Nationally Endangered (Lindenmayer et al., 2017, 2024) (Table 1: at-risk species). Degradation of these keystone structures is widespread even while the extent of forest remains stable.

A second form of forest degradation is the removal of so-called "dangerous trees" for up to 40-m either side of all roads in tall, wet eucalypt forests, a treatment also frequently used in western US forests (DellaSala et al., 2022). Trees considered a risk to firefighters are extensively logged, not only during firebreak construction but also around forestry roads more generally. Such removals are contributing to the scarcity of important wildlife habitat elements with corresponding negative impacts on an array of threatened cavity-dependent fauna (Lindenmayer et al., 2024) and the fragmentation of intact areas (Table 1: landscape characteristics-spatial, temporal).

A third form of forest degradation in this region is post fire and post windstorm "salvage" logging (Fig. 8). Such logging is occurring in many State forests and even in National Parks (in US and Canada this also frequently occurs after fire and insect outbreaks, including within Yosemite National Park). In this case the ecologically beneficial effects of a natural disturbance (fire, insects, windstorms) are overridden by logging and road building that impact many plant and animal species and soils (Lindenmayer et al., 2008; Thorn et al., 2018) (Table 1: ecosystem processes, adaptive potential, nutrient cycling, landscape characteristics). Degradation from post-disturbance logging can mean that forest recovery may not occur for centuries (Lindenmayer and Ough, 2006) (Table 1: ecosystem stability, adaptive potential). Indeed, the Government of Victoria has listed post-fire salvage logging as a Key Threatening Process under its flora and fauna legislation for the State (Victoria Government Gazette, 2024).

Fig. 4. Naturally regenerating ponderosa pine stand (left, high integrity) vs. excessive "fuel reduction" (right, low integrity) deemed as "restoration" on the Santa Fe National Forest, New Mexico. Excessive canopy removals and overly frequent prescribed burning can type-convert forests to open savannahs invaded by flammable invasive species prone to fire spread from overly ventilated canopies (Table 1: adaptive potential, ecological composition) (photo: D. DellaSala).

(a)
(b)
(c)

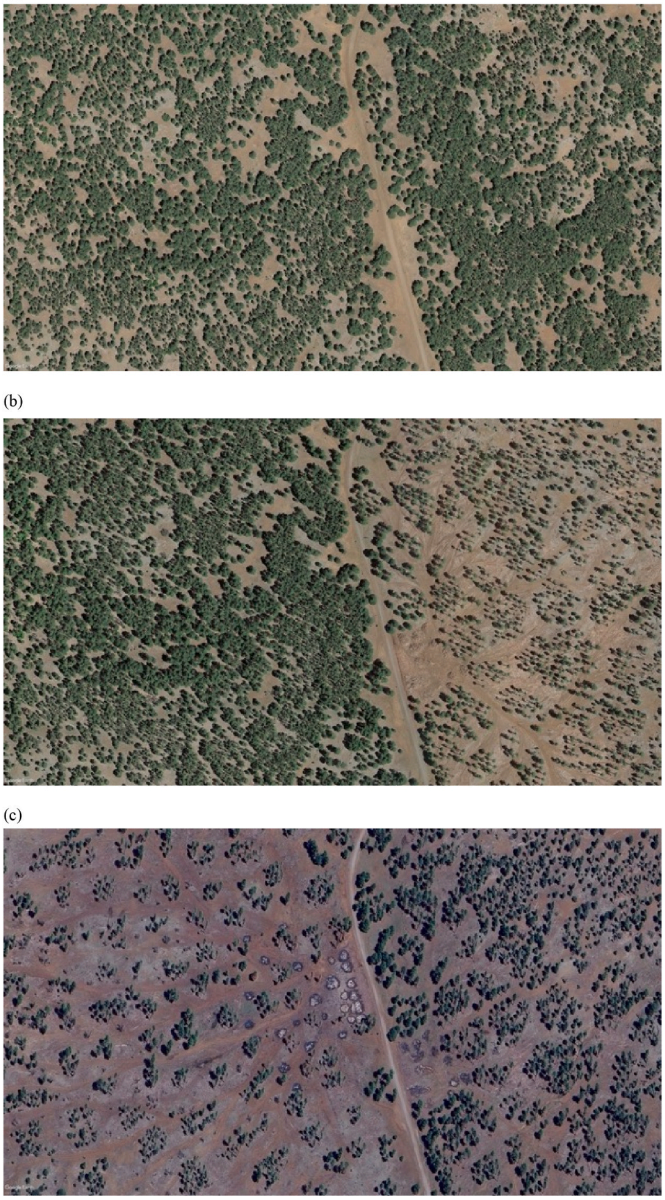


Fig. 5. Google Earth imagery of excessive fuel treatments on the Coconino National Forest, Arizona illustrating landscape scale changes (Table 1: landscape characteristics) showing (a) pre-treatment (2017); (b) commercial thinning (right side) in 2021; and (c) commercial thin (right) and group-selection (left) in 2024. While dry pine forests were naturally open before fire suppression, the degree of biomass removal can act as an 'ecological shock' that type shifts communities into permanently altered states (Table 1: ecosystem stability, adaptive potential) (imagery provided by Bryant Baker, Wildland Maps).

7.5. Degradation of temperate and boreal forests in Europe

About 40 % of the terrestrial continent is forested (European Environment Agency, 2024). While forest cover has been increasing in Europe since World War II (i.e., the Tree Cover Scenario of Gasser et al., 2022), the latest State of Nature report (European Environment Agency, 2023) indicated only 14 % of forests are in "favourable conservation status" (high integrity) within the Natura 2000 network. Logged forest area increased by 49 % while forest biomass loss increased by 69 % from 2016 to 2018 (Ceccherini et al., 2020). The European Union's Bioeconomy Strategy will likely cause further pressure on European forests generally. This is troubling because the European Environment Agency (2024) also reported a doubling of tree canopy mortality from natural disturbances and climate stressors since the late 20th century, which is the equivalent of 1 % of the European Union-27 forest area dying annually. Defoliation rates increased by 10 % while the abundance of forest birds decreased by 3 % between 1990 and 2020 (European Environment Agency, 2024).

Some specific examples of degradation from European countries are as follows.

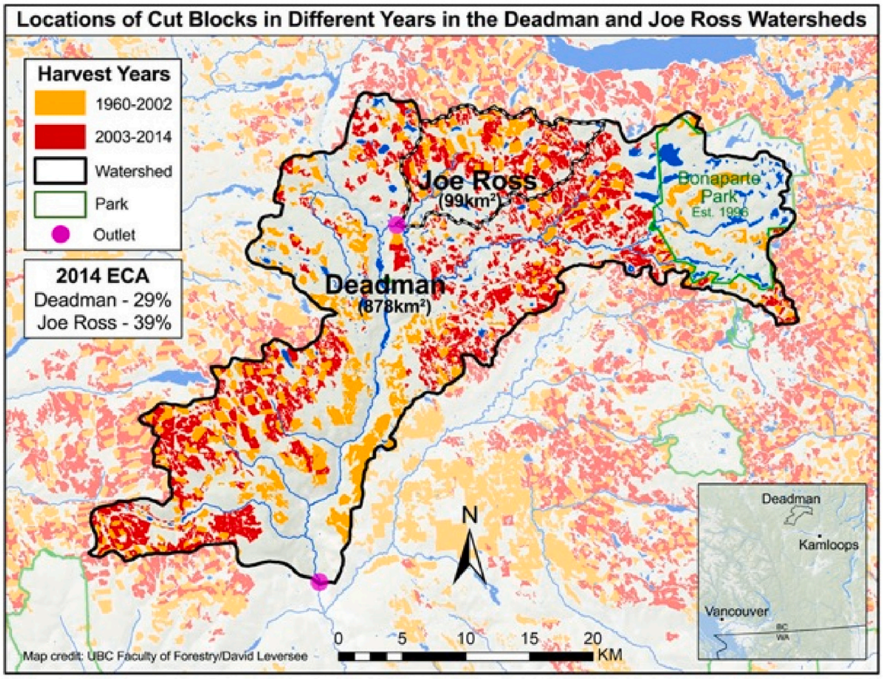
- Almost half of Hungary's forests are monocultures and nearly a quarter are non-native Black locust (*Robinia pseudoacacia*) plantation (NFK, 2023). However, the Minister of Agriculture managed to get Black locust on the list of national treasures as a Hungarikum (uniqueness of Hungary, Hungarikum., 2014). Importantly, Hungary has only 347 ha of natural forest from its reported 2 M forested hectares to serve as reference sites in degradation assessments, illustrating major multiple degradation factors (Table 1: vegetation structure, nutrient cycling, optimal hydro-ecology, characteristic native species, ecosystem stability, adaptive potential, and spatial extent).
- In Austria, the length of forest roads available for logging trucks increased by 40 % since 1996, reaching a total of 218,000 km (Table 1: optimal hydrology, landscape characteristics-road density). The dense network of forest roads used by trucks has a negative impact on the microclimate, wildlife collisions, and the ability of forests to store carbon (Feldbacher-Freithofnig et al., 2024).
- In the four Nordic countries (Denmark, Finland, Norway and Sweden), the extent of forests taller than 15-m declined from logging by 2.25 M ha with the biggest decline rate of 3.5 % of total forests and 20 % of tall forests between 2001 and 2021 (Turubanova et al., 2023) (Table 1: vegetation structure and associated forest age classes).
- In Germany, logging and development resulted in nearly 2 M ha of fragments $<1 km^2$, covering nearly 30 % of total forest area. Fragmentation effects contribute to maximum temperature increases that may push ecosystems to near collapse vs. remaining intact areas that may act as refugia (Mann et al., 2023) (Table 1: adaptive capacity, landscape characteristics-spatial extent). Additionally, removal of tree canopies by as little as 10 % contributed to increased forest temperatures in Scots pine (*Pinus sylvestris*) plantations and European beech (*Fagus sylvatica*) forests (Blumroeder et al., 2021) (Table 1: ecosystem complexity, climate buffering).

Notably, only 2.4 % of the European Union's forests are primary and old-growth forests (Barredo et al., 2021), and most of these forests are not strictly protected (Sabatini et al., 2018). The Białowieża Forest along the Polish-Belarussian borderland is the best example of a temperate lowland primary forest in Europe. However, it has undergone substantial fragmentation from road development and construction of a border wall that has completely blocked movement of large mammals (Fig. 9a, b, c) (Table 1: multiple factors including barriers to wildlife movement). The border wall and associated infrastructure have been accompanied by a general increase in anthropogenic disturbances. These impacts have altered most ecological processes, including natural forest regeneration and herbivory, while jeopardizing nearly all factors in Table 1.

8. Roads as a driver of expansive forest degradation

One of the most pervasive cumulative drivers of degradation globally is the proliferation of roads (Laurance et al., 2014; Ibisch et al., 2016). Up to 25 M km of new paved roads will be constructed globally by mid-century (Dulac, 2013), enough to encircle the Earth >600 times. Roughly 90 % of these new roads will be in developing nations, often in tropical and subtropical regions with outstanding forest integrity

(a)



(b)

Fig. 6. (a) Extensive clearcutting with impacts that accumulate at the landscape scale, increasing the risk of extreme flooding and mass-wasting events (Table 1: ecosystem processes-hydrology; landscape characteristics). The equivalent clearcut area (ECA) is the area that has been clearcut with a reduction factor to account for the hydrological recovery due to forest regeneration and subsequent growth (map credit: D. Leversee, UBC Faculty of Forestry). (b) Clearcut logging and road building in Klanawa Valley, British Columbia, Canada showing extensive degradation via fragmentation effects (Table 1: road density) (photo credit: TJ Watt).

(Laurance et al., 2009). Many new roads are opening up primary forests—promoting influxes of illicit loggers, land grabbers, land speculators, miners, poachers, and illegal-drug producers, among others, many of which operate outside the law and with no environmental oversight (Alamgir et al., 2017; Engert et al., 2024) (Fig. 10).

The expansion of roads is clearly one of the most urgent degradation issues. For instance, China's planet-changing Belt and Road Initiative currently spans a total of 155 nations and is promoting thousands of roads and extractive-industry projects (Laurance, 2017, Ascensão et al., 2018). In Latin America, an ambitious suite of road and other infrastructure projects is advancing, penetrating remote regions and key ecosystems (Laurance et al., 2001; Fearnside et al., 2012, 2013). In Africa, 35 massive 'development corridors' are underway or planned, crisscrossing the continent and collectively exceeding 53,000 km (Laurance et al., 2015). A proposed superhighway in Nigeria would slice through much of the remaining habitat for the critically endangered Cross River Gorilla (*Gorilla gorilla diehli*) (Mahmoud et al., 2017). That highway, which was eventually re-routed following heated public debate, would have generated only questionable economic benefits while allowing the federal government to seize extensive lands owned by traditional communities (Laurance et al., 2021).

Poorly planned road projects not only degrade a large area but can

Fig. 7. A large old tree removed as part of the commencement of the construction of a firebreak in the montane ash forests of the Central Highlands of Victoria (photo: D. Lindenmayer), illustrating the loss of important structures for at-risk species (Table 1: vegetation structure, at-risk species).

Fig. 8. Post-fire "salvage" logging operation in the tall wet forests of the Central Highlands of Victoria is a form of degradation even though trees are planted following logging (photo: D. Lindenmayer). This type of logging alters nutrient cycling, successional processes, post-disturbance structures, native species, ecosystem stability, adaptive capacity, hydro-ecology, soils and is scalable at landscape levels (Table 1).

provoke serious cost overruns, increase corruption, and cause major environmental impacts, while generating sparse or uneven economic benefits that instigate social unrest (Alamgir et al., 2017). Road projects can trigger an array of environmental and societal risks, particularly for lower-income nations where corruption and weak governance undercut efforts to promote sustainability (Laurance et al., 2009). Many developing nations are selling their minerals, timber, and other natural resources or borrowing heavily from international lenders, thereby risking economically damaging debt defaults (Ascensão et al., 2018, Laurance, 2018). There is a significant socio-economic and ecological cost to this type of degradation.

9. Conclusions and Recommendations

9.1. *Degradation monitoring and research needs*

It is vital that improved spatial resolution and on-the-ground monitoring of degradation receive the same support as deforestation monitoring.

Many of the PCIV factors provided herein can be obtained and monitored through remote sensing that is readily available from Landsat and high-resolution imagery from the GEDI ecosystem LiDAR program (https://gedi.umd.edu/; accessed October 27, 2024). Coarse-scale tracking systems are also available on tree cover, intact forest landscapes, and endangered forest locations (https://canopyplanet.org/tools-and-resources/forest-mapper/map; accessed October 27, 2024) along

(a)

(b)

(c)

Fig. 9. (a) Primary forests of the transboundary Białowieża World Heritage Property in Poland and Belarus showing high density of old trees and dead wood. Most of the oak (*Quercus robur*)-lime (*Tilia cordata*)-hornbeam (*Carpinus betulus*) forest on the Polish side is uneven aged, multi-species and multi-layered (photo: A. Wajrak). (b) Logging decks along roads removed in the commercial part of Białowieża Forest in Poland as a response to a bark beetle outbreak. Periodical outbreaks are a natural disturbance and an important ecological process; massive logging and removal of dead trees was ruled illegal by the EU Court of Justice in 2017 (photo: N. Selva). (c) Border wall and associated infrastructure built in 2022 (photo: R. Kowalczyk).

with change detection analyses (e.g., Global Forest Watch, https://www.globalforestwatch.org/; accessed October 27, 2024).

Importantly, there is an urgent need to improve mapping of primary forests to better track degradation in these high conservation value forests. Morphological Spatial Pattern Analysis from the GuidosToolbox can be used to calculate patch statistics (e.g., Vogt and Riitters, 2017) and FRAGSTAT (e.g., Keeley et al., 2021) is available to assess landscape-scale degradation determinations of primary forests. Large-scale forest carbon mapping is also available in some regions (e.g., LANDCARB in the Pacific Northwest, https://research.fs.usda.gov/pnw/products/dataandtools/tools/forest-sector-carbon-calculator; accessed October 27, 2024).

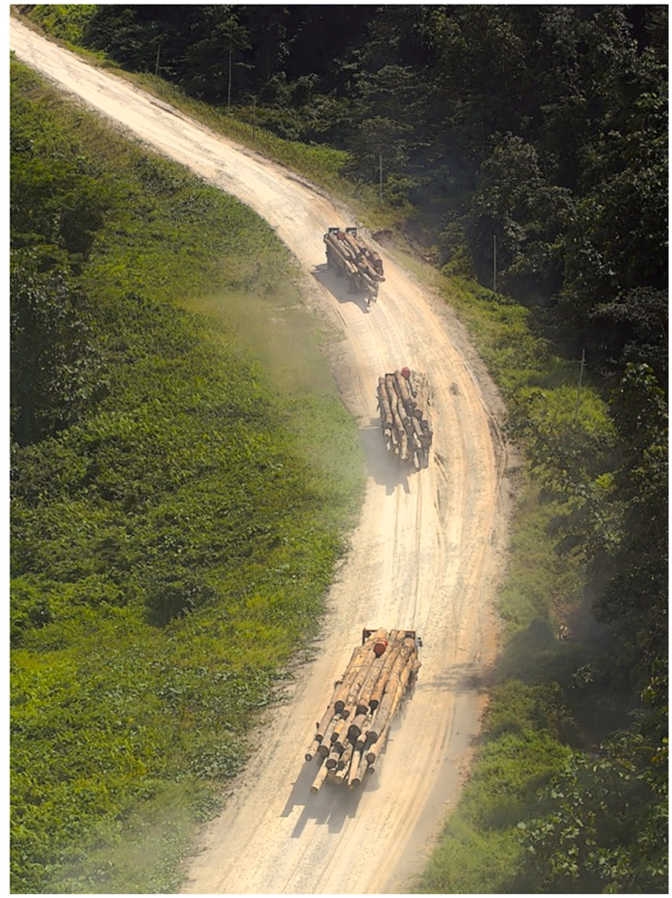


Fig. 10. New roads are opening up many of the world's last remaining intact ecosystems, as evidenced by this forest road in Sabah, Malaysian Borneo (photo: Rhett Butler). Roads have numerous impacts illustrated in Table 1 particularly to hydro-ecology, barriers to wildlife movements, and landscape characteristics related to forest fragmentation.

In other cases, published forestry inventory and plot sampling (e.g., Forest Inventory and Analysis program of the USDA Forest Service) will be needed to determine forest age class and tree size distributions (e.g., as in "timber stand exams"), coarse woody debris for nutrient cycling, carbon stock levels, and soil characteristics. Citizen science can also help with focal taxa determinations (e.g., ebird; https://ebird.org/home; accessed October 27, 2024). Costs of obtaining the necessary information for the PCIV will vary based on whether data are raw or processed, the degree of site-specific sampling involved, and data quality and availability from published datasets. An important follow up is to test the PCIV approach in specific forest types (boreal, tropical wet/dry, wet/dry temperate) using reference versus focal sites that are replicated across scales.

9.2. Degradation avoidance

Meeting the goals of the Paris Climate Agreement and Kunming-Montreal Global Biodiversity Framework requires an urgent policy shift to include the protection and restoration of forest ecosystem integrity. We illustrate a testable process for assessing and monitoring forest degradation that uses an ecosystem integrity framework applied across scales, forest types, and regions and is useful in international agreement compliance. The PCIV framework can also determine when degradation is approaching levels that further exacerbate the biodiversity-climate crisis, including when it is virtually indistinguishable from deforestation. When degradation is assessed as the gross loss of ecosystem integrity, advanced warning can be given to prevent tipping points and cumulative impacts. Examples are provided from forest biomes where the degradation framework can be used in forest reporting by nations, landowners, investors looking for "greener" wood sourcing, and decision makers involved in pledges and international agreements. In this case, the spatial distribution of degradation drivers extends from logging of large, old trees, to skewed young tree age class distributions at the stand and landscape level, and the fragmentation of landscapes by logging, road building, and other developments (Seigel et al., 2023).

We recommend that to better comply with 2030 biodiversity and climate targets, at a minimum, primary and near natural forests with relatively high integrity should be the reference condition that is protected from all forms of degradation and is used as a "blueprint" in restoration efforts aimed at restoring integrity. We emphasize that our framework links ecosystem integrity as fundamental to effective planning and governance (Morgan et al., 2022). As part of our framework, proforestation (Moomaw et al., 2019) could be adopted to assist in recovery of degraded ecosystems that otherwise can become old growth in just a few decades (e.g., mature forests in northeastern US forests, Australia, Europe). Restoration of near-natural forests would make a substantial, more resilient and low-risk contribution to climate mitigation as their integrity would improve over time with the removal of anthropogenic stressors like logging and roads. We also acknowledge that the demonstrated contribution of Traditional Ecological Knowledge to maintaining ecological integrity across forest ecosystems is not formally reflected in our proposed framework. Further collaborative research with Indigenous Peoples would strengthen its implementation.

Degradation, much like deforestation, threatens basic human services and quality of life, and requires integrated solutions to address socio-economic impacts such as related job losses. This can happen by shifting the wood supply out of high integrity forests and into existing purpose planted or other dedicated production forests. To accommodate this transition, investments are needed in increased capacity of existing purposed forests, retooling milling infrastructure for small logs, enabling value-added manufacturing that reduces log exports by keeping more of what is removed locally, and assisting timber reliant communities impacted by industrial automation in milling technologies. An example of where this transition is currently occurring is on the Tongass National Forest in southeast Alaska, where wood supply has been shifting from old-growth forests into previously logged and reforested areas on the designated timber base that is now available for a second rotation on a much smaller logging footprint (DellaSala and Furnish, 2020). The shift is being aided by changes in forest planning and government funding via the Southeast Alaska Sustainability Strategy (2023).

Finally, we provide a transparent and testable assessment framework for assessing and reporting on forest degradation, generating the information needed to meet global forest pledges, implementing forest-climate policies, and supporting relevant procurement strategies. Our framework is urgently needed to slow and even reverse the global biodiversity and climate crisis as many of the world's last primary, near natural forests, and older forests remain vulnerable to preventable anthropogenic losses despite unfulfilled pledges, international agreements, and policies that thus far have failed to sufficiently stem and reverse degradation.

CRediT authorship contribution statement

Dominick A. DellaSala: Writing – review & editing, Writing – original draft, Visualization, Project administration, Investigation, Data curation, Conceptualization. **Brendan Mackey:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Cyril F. Kormos:** Writing – review & editing, Writing – original draft, Validation, Conceptualization. **Virginia Young:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Julee J. Boan:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Jennifer L. Skene:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **David B. Lindenmayer:** Writing – review & editing, Writing – original draft, Visualization, Validation, Conceptualization. **Zoltan Kun:** Writing – review & editing, Writing – original draft, Visualization. **Nuria Selva:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Jay R. Malcolm:** Writing – review & editing, Writing – original draft, Conceptualization. **William F. Laurance:** Writing – review & editing, Writing – original draft, Visualization.

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Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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