WCS High Integrity Forest (HIFOR) Investment Initiative: The Science Basis[a]

Forests and Climate Change Program
Wildlife Conservation Society, November 2023

[a] This working document was produced as part of the High Integrity Forest (HIFOR) Investment Initiative within the WCS Forests & Climate Change Program. For additional HIFOR documents, see: https://www.wcs.org/our-work/forests-and-climate-change/hifor. For further information regarding this document, contact Tom Evans, Senior Director for Forest Conservation, WCS Forests & Climate Change - tevans@wcs.org

Executive Summary

This brief describes the science basis for the High Integrity Forest (HIFOR) Investment Initiative. The initiative aims to create a new climate and biodiversity asset class to help finance the protection of high integrity tropical forests — those that are least degraded by human impacts — on the basis of their role in climate change mitigation and biodiversity conservation. The HIFOR Unit represents a hectare of well-conserved, high integrity tropical forest. Associated with this unit are metrics that quantify climate regulation benefits (in terms of the number of tons of net CO_2 removals into forest biomass over the course of a decade) and biodiversity conservation benefits (in terms of the number of hectares of high biodiversity forest maintained with high integrity over a decade).

Large, remote, high integrity forests, and hence the services they provide, are often wrongly perceived to be safe from human pressures, but in fact face substantial and growing risks, and so their protection represents a critical conservation priority. For example, from 2017 to 2021 the extent of high integrity tropical forest declined by about 3.1% per year. Infrastructure expansion, logging, agriculture, fires, mining, and hunting all drive this trend.

Natural ecosystems worldwide, primarily forests, reduce the impact of anthropogenic GHG emissions by absorbing ~30% of anthropogenic CO_2 emissions. Carbon uptake by this "land sink" is distinct from the uptake associated with forest restoration, which is accounted for as part of "net land use change." The action of this sink (currently 11.4 $GtCO_2$ per year; 765 $GtCO_2$ since 1850) has probably prevented around 0.6°C of global warming. Tropical forests mapped as 'high integrity' likely contribute around 1.8 $GtCO_2$ per year to the land sink. The strongest average removals in high integrity tropical forests are found in Africa (2.9 $tCO_2\ ha^{-1}\ yr^{-1}$), followed by Asia (2.0 $tCO_2\ ha^{-1}\ yr^{-1}$) and the Americas (1.1 $tCO_2\ ha^{-1}\ yr^{-1}$). Deforestation and degradation are eroding the area that contributes to the sink, whilst climate change and other factors are slowing the rate of carbon removals in some remaining areas.

Loss or degradation of high integrity forest cover in the tropics typically causes additional climate warming, quite apart from the carbon impacts, by altering land surface energy and moisture exchanges. These biophysical processes increase the estimated warming effect of tropical deforestation or degradation by about half compared to counting only CO_2 emissions. Total deforestation in the tropics could increase global warming by around 0.28°C (at least 0.11°C of this from high integrity forests) through biophysical effects alone. These biophysical effects also promote local climate stability, lowering average peak temperatures in nearby areas by around 1.0°C (range 0.2-2.4°C depending on locality) and reducing extreme temperatures by substantially more.

Higher ecological integrity correlates with higher biodiversity. High integrity forests support consistently higher numbers of forest-dependent species, ensure lower extinction risk for the species present, support higher genetic diversity within species and lead to a lower risk of ecosystem collapse. Loss of integrity has an impact on the many functions (often called services) an ecosystem performs. High integrity forests are also better able to cope with climate change and other stresses.

In addition to the climate regulatory functions and biodiversity values that this brief focuses on, high integrity forests embed many other environmental values, including large carbon stocks, regulation of local and regional hydrology, decreased risk of zoonotic disease spillovers, and contributions to the livelihoods and cultures of Indigenous Peoples and other local communities.

High integrity forests have long helped to buffer us against the worst effects of climate and biodiversity crises. If we are to meet the 1.5-degree goal, halt human-caused extinctions and prevent the collapse of many ecosystems, it is essential that we invest in their protection.

Glossary of selected key terms

Albedo: The amount of solar radiation that is reflected by the surface of a forest or other land use. It plays a significant role in the Earth's energy balance.

Anthropogenic: Any process, effect, or phenomenon that is attributable to humans. Forest loss (or conversely, recovery) is anthropogenic if attributable to, for example, increases (/decreases) in a human activity such as logging.

Biodiversity: The United Nations Convention on Biological Diversity (CBD) defines biodiversity (also called biological diversity) as the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.

Biophysical effects: Beyond their role in the carbon cycle, forests regulate local, regional, and global climate by modulating the exchange of moisture and energy between the land and the atmosphere. By altering these exchanges, changes in forest cover and condition can cause warming or cooling effects, referred to as biophysical effects[1].

Deforestation: Removal of tree cover resulting in a parcel of land falling below the accepted definition of forest in a given region.

Degradation: Reduction in the condition of a forest that does not result in deforestation, i.e., loss of tree cover, or other declines in the structure and functions of a forest area, that do not result in the parcel falling below the relevant forest definition.

Ecological integrity: The degree to which an ecological system remains undegraded and so supports and maintains a community of organisms and associated abiotic characteristics that have composition, structure, and functions within the natural range of variation for an ecosystem of that kind in that region[2].

Evapotranspiration: The combined process of water vapor being released into the atmosphere through both evaporation from surfaces like soil and water bodies, as well as transpiration from plants through their leaves and other organs. It plays a crucial role in the water cycle.

Forest Landscape Integrity Index (FLII): The FLII[3] is an indicator of the ecological integrity of a forest, as measured mainly by the level of significant human-induced disturbances affecting it.

High Integrity Forest: A forest where the structure, composition and function are very close to their natural range of variation, free from significant impact due to intensive human activities. The FLII classifies high integrity forests as those with a score of > 9.6 (on a scale from 0 to 10).

Intact Forest: We use this term here in the same sense as it is used in a series of key recent papers on forest dynamics that synthesize data from pantropical networks of permanent plots [4,5,6], i.e. forests free from significant human-induced degradation, such as logging or past clear-cutting.

Land sink: Net absorption of CO_2 by a terrestrial ecosystem, such as a forest or wetland, that is not attributable to any kind of anthropogenic land use change.

Land Use Change: The range of human impacts on land that are often referred to as 'land use, land-use change and forestry', including transitions of land between major land use categories as well as human modification of the land within a category.

REDD+: A set of voluntary initiatives and policies aimed at addressing deforestation and forest degradation in developing, mostly tropical, countries. It stands for Reducing Emissions from Deforestation and Forest Degradation, as well as Conservation, Sustainable Forest Management, and Enhancement of Forest Carbon Stocks, although in practice it has focused primarily on avoided deforestation.

Sink/Absorption/Removals: Forests absorb CO_2 from the air through photosynthesis and then release it through respiration, mortality, and decay. In the balance between these processes, stores of carbon can increase (or decline) in the ecosystem. An increase of carbon storage is commonly called a sink. This sense of the word is interchangeable with the terms *absorption* and *removals*. The term *sink* is also confusingly used by some other authors to refer to a standing stock of carbon but we avoid that usage here.

Introduction

This brief describes the science basis for the High Integrity Forest (HIFOR) Investment Initiative[b]. High integrity forests — those that are least degraded by human impacts[c] — have long served as a buffer against the worst effects of the climate and biodiversity crises. The HIFOR initiative aims to create a new climate and biodiversity asset class to help finance the protection of high integrity tropical forests on the basis of their role in climate change mitigation and biodiversity conservation.

The **HIFOR Unit** represents a hectare of well-conserved, high integrity tropical forest. Associated with this unit are metrics that quantify climate regulation benefits (in terms of the number of tons of net CO_2 removals into forest biomass over the course of a decade) and biodiversity conservation benefits (in terms of the number of hectares of high biodiversity forest maintained with high integrity over a decade)[d]. This brief summarizes the evidence for the role of high integrity tropical forests in each of three processes: (1) net carbon absorption, (2) biophysical cooling that occurs independently of carbon absorption, and (3) biodiversity conservation[e].

The climate cooling effects for which high integrity forests globally are responsible have kept the Earth roughly 0.6˚C cooler than it would be without them. Such a difference, greater than that between 1.5 and 2 degrees of global warming, has an estimated impact on the global economy in the trillions of dollars[7], but the value of that ecosystem service is currently priced at zero. Hence, the current market failure is enormous, as is the opportunity to correct it.

Existing climate finance mechanisms such as REDD+ are ill-suited to support the management and protection of high integrity forests because they are designed primarily to mobilize funds to reduce deforestation based on historic rates of forest loss. In contrast, HIFOR is designed to incentivize investments to prevent the advance of deforestation and forest degradation into areas where they are not yet prevalent[f]. In this sense, HIFOR is complementary to REDD+ mechanisms in the same way that investments in preventive health care initiatives complement investments in urgent/ emergency care, with both being essential to a functional public health system.

In contrast to REDD+ units, HIFOR Units are not considered suitable for use for offset purposes that 'compensate' directly for a portion of the emissions caused by the purchasing entity. This is because the way that they are estimated does not require a demonstration that each ton of removals was additional on at least a one-to-one base to what would have happened in the absence of the funded conservation program. Nonetheless, as shown in this brief, high integrity forests face significant and growing threats and their future is far from secure, so the investments catalyzed will substantially increase the likelihood that the services provided by the forests continue. As such, HIFOR Units

[b] We acknowledge extensive support received in the research and drafting of this document from David Landholm, Simon König, Gabriela Martinez and Charlotte Streck (Climate Focus), Scarlett Benson and Talia Smith (SYSTEMIQ) and Deborah Lawrence (University of Virginia).

[c] Please see Glossary, page 2, for selected key terms.

[d] See the primer *Creating Economic Incentives for the Conservation of High Integrity Tropical Forests* (WCS, 2022).

[e] For an expanded treatment of the evidence summarized here, see *WCS High Integrity Forest Investment Initiative (HIFOR): A Review of The Science* (WCS 2023)

[f] See the brief titled *High Integrity Forest Removal Units vs. Forest Carbon Credits. Similarities and Differences* (WCS, 2022).

represent a contribution made by the purchaser towards overall global climate change mitigation efforts.

A forest has high ecological integrity if its structure, composition and function are free from significant impact due to intensive human activities such as large-scale commercial logging, infrastructure development, mining, or farming[8,9,10]. Ecological integrity varies on a continuous scale, so defining 'high' integrity implies setting a threshold somewhere on this continuum. There have been various approaches to operationalize this concept using a wide variety of related terms. In this brief, and in the development of the HIFOR initiative, we use the map of high integrity tropical forests as defined by the Forest Landscape Integrity Index[3], which encompassed approximately 766 million hectares in 2021.

High integrity forests embed many other environmental values beyond the scope of this brief, including storage of large carbon stocks, regulation of local and regional hydrology, decreased risk of zoonotic disease spillovers, and contributions to the livelihoods and cultures of Indigenous Peoples and other local communities[10,11,12,13,14].

Threats to high integrity tropical forests and their services

In 2021, 6.8 Mha of forest were lost, 96% of them in the tropics[g]. 3.7 Mha of losses were from humid primary tropical forests with relatively high ecological integrity. While these active deforestation frontiers are undoubtedly key priorities for conservation investment, large, remote, high integrity forests also face substantial and growing threats, especially from degradation[15,16], and so also merit significant investment. Infrastructure expansion, logging, agriculture, anthropogenic fires and hunting all play a role. For example, the extent of high integrity tropical forest has declined at about 3.1% per year during 2017-2021 (Forest Landscape Integrity Index; WCS unpublished data). Similarly, tropical hinterland forests, core areas distant from recent active clearance and larger than 100 km^2, declined at 3% per year during 2007-2013[16]. The largest blocks of high integrity forest (>500 km^2; termed Intact Forest Landscapes) declined by 12% between 2000 and 2020 with higher rates of decline in more recent years compared to earlier in the period[h,17]. There are many indicators that threats to forest integrity will be sustained or increased into the future[18,19,20].

These threats to integrity cause significant impacts to the critical ecosystem services described later in this brief. For example, the sum of all historical deforestation (not counting forest degradation) has made the global land sink about 2.6-3.3 $GtCO_2\ yr^{-1}$ smaller than it otherwise would have been[21]. Considering an aspect of more recent impacts alone, the 28 million hectares of high integrity tropical forests damaged or destroyed from within Intact Forest Landscapes between 2000 and 2013 could likely have sequestered an additional 3.6 $GtCO_2$ by 2050 if left undisturbed[15]. The loss of integrity has weakened the intact forest sink in Borneo (and presumably throughout the tropics) via edge effects, with reduced sinks up to 450 m in from an edge, and zones less than about 300 m from an edge becoming average net sources[22]. Defaunation also seems likely to have a pervasive effect on

[g] https://forestdeclaration.org/resources/forest-declaration-assessment-2022/
[h] Trends updated to 2020 here https://www.wri.org/insights/worlds-last-intact-forests-increasingly-fragmented

the strength and resilience of the sink, as it has been shown to negatively affect long-term forest carbon dynamics[23,24,25].

Global biodiversity decline is also heavily driven by anthropogenic threats to forests[26] with effects from wildfires, overhunting, logging and biological invasions, alongside other stressors[27,28]. Beyond outright forest clearance, which is the greatest threat facing forest biodiversity[29], degradation from logging is the most pervasive threat facing species inhabiting high integrity forests[17]. Whilst logged forests can retain significant ecological value, many species are sensitive to logging, and studies across many taxonomic groups have shown impacts increasing with the intensity of logging and with the number of times a forest has been logged[30]. Fragmentation (along with the associated edge effects) is also a severe threat to forest-dependent species[31,32]. Often the first form of integrity loss to affect a forest is over-hunting[33,84]. Even within tropical Intact Forest Landscapes, 52% of the area is predicted to have experienced significant declines in hunted vertebrates[34]. For example, the African forest elephant, an ecological keystone species, has been hunted out from more than 75% of the areas it used to occur, with severe declines in the remainder[35].

There are also widely observed compounding interactions between the direct and indirect threats outlined above[27,36]. Logging increases access for hunters, and when combined with fragmentation logging damage also has more severe impacts on biodiversity because many species need larger areas of habitat and/or connectivity across the forest matrix to survive[30]. Fragmentation increases fire frequency (e.g., in the remaining forests of lowland Sumatra[37]), degradation increases vulnerability to periodic severe droughts (e.g., in the Amazon[38]) and forest carbon stocks are likely to be more resilient to loss driven by moderate climate change if they are protected from direct impacts such as clearance, logging, or fires[39].

Net carbon absorption by high integrity tropical forests

Global carbon accounting typically distinguishes two sink pathways into ecosystems. First, net carbon absorption can occur after an anthropogenic land-use activity that damages forests is slowed or reversed, allowing recovery. Carbon sinks associated with reforestation and restoration are not considered further in this brief. There is also a large carbon sink in many long-established ecosystems. This 'land sink'[21,14] mainly occurs in high integrity forests and results primarily from enhanced growth due to recent environmental changes (especially fertilization effects associated with high CO_2 levels).

On average, over the past decade, the land sink has removed an estimated 29% of annual global anthropogenic carbon emissions, equal to 11.4 $GtCO_2$ yr^{-1} (+/- 2.2)[21], mostly in forests. This sink mainly involves the above ground and below ground living biomass of trees and is studied using long-term plots[40]. Without the continued functioning of this sink, climate change would be occurring significantly faster than it currently is[41]. The estimated cumulative land sink is 765 $GtCO_2$ since 1850[21]; if this had not been removed from the atmosphere by terrestrial ecosystems, we estimate there could have been an additional 0.6°C increase in global temperatures beyond what has been observed[i] and hence the Earth would already have exceeded the 1.5°C target of the Paris Agreement.

Within this broader global land sink, sinks into the biomass of forests in the tropics which are 'intact'[j] have been estimated at 2.49 $GtCO_2$ yr^{-1} (range 0.62-4.25), during the period 2010-2020[6] (Table 1). Adding the coupled increase in deadwood and litter pools[k] would raise the value slightly to 2.69 Gt $GtCO_2$ yr^{-1}. There is potentially also a sink into the soils under these forests, but that remains largely unstudied. This tropical intact forest sink is at least 24% of the overall global land sink mentioned above and as such counteracts about 7%[l] of all human-caused emissions each year. Much of the remainder of the land sink occurs in intact boreal forests[42] with some also occurring as boosts to regrowth rates in degraded or managed forests, or in non-forest ecosystems.

Table 1. Estimated total size of the land sink into intact tropical forests.

	Units	2000-2010	2010-2020	2020-2030	2030-2040
Pantropical	***$GtCO_2$ yr^{-1}***	**3.63**	**2.49**	**1.72**	**1.06**
Africa	*$GtCO_2$ yr^{-1}*	*1.69*	*1.36*	*1.14*	*0.95*
Amazon	*$GtCO_2$ yr^{-1}*	*1.65*	*0.92*	*0.44*	*0.00*
Asia	*$GtCO_2$ yr^{-1}*	*0.26*	*0.22*	*n/r*	*n/r*

Source: Hubau et al. (2020)[6] using observations to 2015 and projections thereafter. Includes above and below ground biomass, including smaller trees and lianas, but not litter, deadwood, or soils. 'n/r' = not reported.

Despite recent declines, Table 1 shows that intact forests in all three tropical regions continue to provide overall net removals.

There were an estimated 1,200 million hectares of 'intact' forests across the tropics in 2020, although no map is available[6]. As a step towards defining more explicitly the locations where this sink is occurring, tropical forests mapped as having high ecological integrity according to the Forest Landscape Integrity Index (FLII)[3] cover 766 million hectares in 2021. We estimate that they are likely to provide an annual sink of at least 1.76 $GtCO_2$, which is 67% of the overall estimated tropical intact forest sink[m]. As such, the high integrity forests we have mapped (Figure 1) should represent the core of any efforts to conserve this sink.

Table 2 summarizes estimates of the average annual net CO_2 sink per unit area in intact/high integrity forests. The sink intensity is quite small compared to the size of the stock (<1% yr^{-1}) thereby creating measurement challenges. Nonetheless, it can be very significant in aggregate. Large individual protected areas[44] or Indigenous territories[14,45] can be responsible for millions of tons of CO_2 removals per year so maintaining each of them represents a significant and necessary contribution to slowing climate change, especially as there is strong evidence that these critical forests are being eroded[46,47].

[i] For methods, see the more detailed HIFOR Science Review cited in the Introduction (available upon request).
[j] Defined in the source studies as being 'structurally intact and largely free of anthropogenic pressure'.
[k] We assume that over the medium term the ratio of deadwood and litter to biomass will remain broadly constant.
[l] i.e., 24% of 29%
[m] Using a stratify-and-multiply approach to cross-tabulate the area of forest in the High category of the FLII in each forest type within each region versus the relevant removal rate reported by[43]

Table 2 Estimated average annual net CO_2 sink into intact tropical forests

	Source	Units	2000-2010	2010-2020	2020-2030	2030-2040	*IPCC defaults^*
Pantropical	**1**	***tCO_2 ha^{-1} yr^{-1}***	**2.29**	**1.74**	**1.38**	**0.96**	***n/r***
Africa	1, 3	tCO_2 ha^{-1} yr^{-1}	3.21	2.89	2.70	2.52	2.80
Amazon	1, 3	tCO_2 ha^{-1} yr^{-1}	1.74	1.05	0.55	0.00	2.15
Asia	2, 3	tCO_2 ha^{-1} yr^{-1}	*n/r*	1.97	*n/r*	*n/r*	1.51

Sources: 1: Hubau et al. (2020)[6]; 2: Qie et al. (2017)[22]; 3: Requena-Suarez et al. (2019)[43]. Includes above and below ground biomass, trees only. n/r = not reported. ^Dates not specified, data mostly from 1990-2019[43].

Whilst globally the total land sink is increasing[n,21,48], recent and projected declines in the tropics can be seen in Table 1. This is partly due to direct human factors such as deforestation and degradation reducing the extent of forest that contributes. But even in undegraded forests the sink intensity per hectare, averaged across tropical regions, is declining, particularly in the Amazon Basin (Table 2).

Trends in the sink in tropical forests are driven mainly by environmental changes, especially CO_2 concentrations and climate change (e.g. worsening droughts), together with some intrinsic factors linked to tree demography[6]. The relative strength of these factors appears to vary geographically and through time, can lead to increases as well as decreases in sink strength, and is a very active area of research. Some forests may partially adapt to changing climates[49].

Deforestation and forest degradation affect total sink size in all three tropical regions but sink intensity in the remaining intact forests is taking a different path in South America compared to Africa, with unclear trends in Asia due to sparse data. Average sink intensity in African intact forests increased slightly in past decades, peaked recently, and is projected to decline slightly, by around 14%, from 2010 to 2030[6]. By contrast, average sink strength across intact South American forests (principally the Amazon) has substantially declined already and is projected to reach zero or even tip into a net source, perhaps sometime in the 2030s[5,6,50].

Sink trends over time also vary *within* the key tropical regions, although the patterns cannot yet be quantified robustly. For example, in Amazonia the strongest declines appear to be at the southern and eastern margins, which have always been hotter and drier than areas to the north and west, and hence closer to key tipping points. Forests in parts of that zone are already suspected to have transitioned to net CO_2 emission[51]. However, sinks apparently remain stronger and more resilient in the cooler and wetter north and west[51]. Large areas dominated by old-growth forests also recently showed an increase in aboveground biomass in the southwest Amazon[52], perhaps counter-intuitively as a response to recent severe droughts[53,54,55,56]. Other less studied areas such as mature montane forests in the Andes have also recently been described as major carbon sinks that should be preserved[57].

[n] According to the IPCC, under all scenarios with increasing CO_2 emissions the land sink will increase in absolute terms, driven especially by an increase in the boreal component. However, this will represent a progressively smaller percentage of total anthropogenic emissions, so a growing share of emissions will stay in the atmosphere.

Biophysical cooling by high integrity tropical forests

Loss or degradation of high integrity forest cover in the tropics typically causes additional climate warming, apart from the carbon impacts, by altering land surface energy and moisture exchanges. These have effects on temperature at local, regional and global levels. The dominant processes in tropical forests are evapotranspiration and canopy roughness, whose combined cooling effects outweigh the warming effect of dark green forests having a lower albedo (reflectivity) than cleared land[8,58]. Forests efficiently move water from the land surface to the atmosphere via evapotranspiration through their deep roots and high leaf area, converting sensible heat into latent heat as they do so. This is strongly enhanced by the uneven nature of tropical forest canopies (i.e., canopy roughness), which draws heat and water vapor from the surface into the upper atmosphere by vertical mixing of turbulent air. As this water vapor condenses higher in the atmosphere, the latent heat is converted back to sensible heat[59]. Thus, the warming that began with sunlight hitting the canopy ends up having its main effect high in the atmosphere while the forest keeps the surface temperature considerably lower than it would be otherwise.

Including the loss of these biophysical processes increases the warming effect of tropical deforestation or degradation by about half compared to counting the effect of CO_2 emissions alone. It is estimated that total deforestation in the tropics would increase global temperatures by around 0.28°C[58] (at least 0.11°C of this from high integrity forests[o]) through biophysical effects alone[p].

These biophysical effects also promote *local* climate stability by lowering average peak temperatures in nearby areas by around 1.0°C (range 0.2-2.4°C depending on locality) and reducing local extreme temperatures by substantially more[58,62,63,64,65]. This underlines the importance of tropical forests not only for global climate change mitigation but also for adaptation to changing climates by people and ecosystems at local scales. There are serious practical implications, for example the fact that human exposure to local heat stress effects linked to deforestation can be as bad as, and additional to, the effects associated with severe global climate change scenarios[66,67].

The importance of high integrity tropical forests for biodiversity

Biodiversity is important both because of its intrinsic value and because it underpins a huge range of ecosystem functions that are critical for human well-being including the production of food, fibre and fuel, cycling of nutrients, carbon and water, seed dispersal, pollination, pest resistance, promotion of mental wellbeing, among others[68]. Despite the complexity inherent in measuring biodiversity, the consistent finding across most studies is that human actions that modify forests (and so reduce their integrity) lead to poorer biodiversity on most measures, with stronger

[o] High integrity forests represent 38% of all tropical forests, 38% of 0.28°C = 0.11°C. In reality, loss of high integrity forests could have a disproportionately higher impact on warming.
[p] Forests also produce volatile organic compounds which interact with cloud formation, thereby forming another pathway by which deforestation and degradation might induce warming, but there are still large uncertainties around the size of this effect[58,60,61]

modification leading to greater declines[q,r] [10,69]. Because biodiversity varies so much across the Earth's surface, the scale of these negative impacts varies greatly from place to place, with one of the areas of greatest vulnerability being the high integrity tropical forests which contain most of the Earth's biodiversity[68,70]. Selected published examples are outlined below. Higher ecological integrity correlates with higher biodiversity at the level of species, of genes, and of ecosystems. As such, high integrity forest:

- **Supports consistently higher numbers of forest-dependent species** than degraded forest[27,31,69,71,72,73]. Even for forest species that persist for a time in degraded fragments, high integrity forests may be necessary to ensure their persistence over the long term[74,75,76].
- **Ensures consistently lower extinction risk for the forest species present**[77,78]. For example, a global analysis of nearly 20,000 vertebrate species showed that even minimal initial deforestation within an Intact Forest Landscape exacerbated extinction risks[28].
- **Supports higher genetic diversity within species**. This has potentially significant benefits for enabling ongoing evolutionary change and adaptation[79].
- **Leads to a lower risk of ecosystem collapse**. Reduced integrity is a key indicator for risk of ecosystem collapse (analogous to species extinction) in the Red List of Ecosystems[9].

Loss of integrity harms many functions (often called services) that an ecosystem performs. As such, high integrity forests:

- **Display higher functional diversity**. Degradation pressures can lead to changes in the kinds of ecological traits present in animal and plant communities[s], which can in turn affect ecosystem functioning[35,80]. Biodiversity loss reduces the efficiency by which ecological communities capture biologically essential resources, produce biomass, decompose, and recycle biologically essential nutrients[81].
- **Are more likely to support key processes in species' life cycles**. For example, loss of ecological integrity often leads to decline or loss of vertebrate fruit dispersers and pollinators, altering the composition of the vegetation and putting some plants at risk of extinction[25,82].
- **Are more effective at sustaining large-scale ecological processes**. For example, natural disturbance regimes that sustain habitat resources, constitute selective forces to which species are adapted, or otherwise influence community composition[30,71,80].

---

[q] Some aspects of biodiversity do increase with integrity loss, but they typically involve the presence or abundance of species that are not forest-dependent and are assigned lower value in most assessments because they are more widespread, less threatened and have less specialized ecological roles. In a subset of cases the species or ecosystem states that benefit in this way may be highly valued, economically or culturally – for example in the creation of certain 'cultural landscapes'.

[r] The number of species that are threatened with extinction in a region is often higher where integrity has been severely reduced, and whilst the persistence of these species is in one sense a valuable aspect of the biodiversity of those forests, the fact that they are threatened at all is evidence of severe underlying harm to biodiversity. Refugia for threatened species in such regions are often associated with local (though not global) maxima of integrity.

[s] e.g., ability to use certain nutrients efficiently, tolerate certain environmental extremes or photosynthesize under particular conditions.

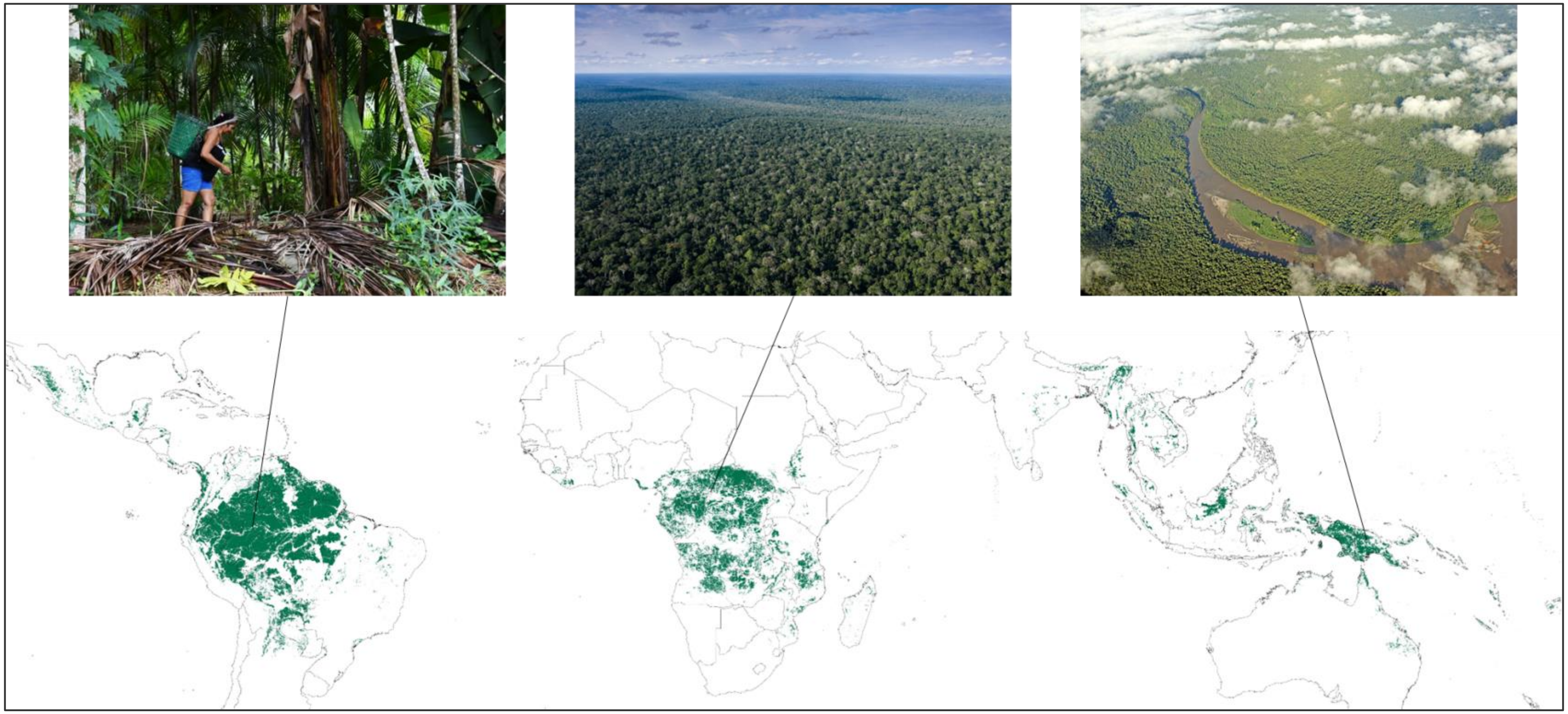

Figure 1. Approximate extent of high integrity forests in the tropics in 2021. These were defined using a score of ≥ 9.6 units of the Forest Landscape Integrity Index[3]. The best-preserved areas are often within Indigenous lands (top left: Amanã Sustainable Development Reserve, Brazil © Yahoo photos). High integrity forests constitute large blocks of continuous cover that act as carbon sinks (top middle: Djéké triangle, a forest area adjacent to the Nouabalé-Ndoki National Park in Republic of Congo © S. Ramsay – Wildlife Conservation Society) and are key areas for climate and hydrological regulation at multiple scales (top right: Aerial view of high integrity forests of Papua New Guinea © iStock photos).

Resilience includes the ability of a system to return to its original state after change or, in extreme cases, to adjust to sustained pressures whilst retaining its essential character and functions. High integrity forests:

- **Contain larger, healthier populations of individual forest-dependent species**. These provide greater options for local adaptation and phenotypic plasticity in response to rapidly changing environmental conditions[79,83,84].
- **Provide more options for species to disperse or retreat to refugia**. Ecosystems with good connectivity typically span environmental gradients such as latitude, altitude, rainfall or temperature, enabling gene flow and migration to track shifting climates[85,86].
- **Offer refuges from increased fire regimes in degraded landscapes under changing climates**. Intact forests act as fire refuges in landscapes where non-intact forests burn too frequently for species dependent on long time intervals between burning[87,88].

Conclusions

This brief details three key examples of the many indispensable services provided by high integrity tropical forests, namely: contributing to the land sink (which removes a large proportion of humanity's carbon emissions); generating biophysical cooling effects (whose loss leads to both global and local warming); and providing a refuge for biodiversity.

As such, high integrity forests represent critical natural infrastructure, yet the evidence presented here also shows that they face serious, diverse, and sustained threats. Modelled economic and policy pathways that enable human society to achieve the global temperature goals of the Paris Agreement assume that the foundational services currently provided by high integrity forests will largely be sustained, but this cannot be taken for granted without deliberate and large-scale protective measures.

High integrity forests have long helped to buffer us against the worst effects of climate and biodiversity crises. If we are to meet the 1.5-degree goal, halt human-caused extinctions and prevent the collapse of many ecosystems, it is essential that we invest in their protection.