Policy Options for the World's Primary Forests in Multilateral Environmental Agreements

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Abstract

We identify policies that would provide a solid foundation in key international negotiations to ensure that primary forests persist into the 21st Century. A novel compilation of primary forest cover and other data revealed that protection of primary forests is a matter of global concern being equally distributed between developed and developing countries. Almost all (98%) of primary forest is found within 25 countries with around half in five developed ones (USA, Canada, Russia, Australia, and NZ). Only ∼22% of primary forest is found in IUCN Protected Areas Categories I–VI, which is approximately 5% of preagriculture natural forest cover. Rates of deforestation and forest degradation are rapid and extensive, and the long-term integrity of primary forest cannot be assumed. We recommend four new actions that could be included in climate change, biodiversity, and sustainable development negotiations: (1) recognize primary forests as a matter of global concern within international negotiations; (2) incorporate primary forests into environmental accounting; (3) prioritize the principle of avoided loss; and (4) universally accept the important role of indigenous and community conserved areas. In the absence of specific policies for primary forest protection, their unique biodiversity values and ecosystem services will continue to erode.

Introduction

Despite the international attention paid to deforestation, forest degradation, and improving forest management, primary forests continue to decline rapidly due to ongoing land-use encroachment (OECD 2006; Karp & Richter 2011), and their future cannot be assumed (Laporte *et al.* 2007). Primary forests are globally irreplaceable with unique qualities that make significant contributions to biodiversity conservation, climate change mitigation, and sustainable livelihoods (Foley *et al.* 2007). Off the international community's policy agenda, however, is how to maintain the integrity of the world's remaining primary forests. Deficiencies in international forest policy can be rectified over coming years but the window of opportunity provided in relevant negotiating forums is short-lived.

Here, we identify four new actions that would provide a solid policy foundation for key international negotiations, including forest-related multilateral environmental agreements, to help ensure that primary forests persist into the 21st Century: (1) recognize primary forests as a matter of global concern within international negotiations; (2) incorporate primary forests into environmental accounting; (3) prioritize the principle of avoided loss; and (4) universally accept the important role of indigenous and community conserved areas. We first provide an update on the current distribution and condition of the world's primary forest.

Forest distribution and condition

Along a human-use continuum, three categories are recognized: (i) primary forests—naturally regenerated forest of native species, where there are no clearly visible indications of human activities and ecological processes are not significantly disrupted; (ii) forests used for industrial logging and where there are clearly visible signs of human activities but where forests are reliant on natural regeneration processes ("production forests"); and (iii) planted forests predominantly composed of trees established through planting and/or deliberate seeding of commercial varieties ("plantation forests") (FAO 2010). The Collaborative Partnership on Forests, an informal, voluntary arrangement among 14 international organizations and secretariats with substantial programs on forests that supports the work of the U.N. Forest Forum, also uses these three categories of forests. Primary forest therefore can be defined as natural forest largely undisturbed by industrial-scale land use. "Intactness" is a measure of the degree a natural forest landscape has been degraded and fragmented by human land use (additional material on the definition of primary forest and intact forest landscapes is provided in Supporting Information). Of the world's extant 40.1×10^6 km^2 of forest, some 57% is subject to industrial logging or designated for multiple uses including wood production, 7% is plantation, and around 36% (14.5×10^6 km^2) is primary forest (FAO 2010).

We completed a novel global compilation of primary forest cover, building on the global survey of Potapov *et al.* (2008) (see Supporting Information for details of materials and methods). The results and associated world map revealed that of the $\sim 13.1 \times 10^6$ km^2 of intact forest landscape (i.e., primary forest in contiguous blocks >500 km^2), 50% occurs in snow/polar regions; 46% in equatorial areas; and 3% in warm temperate climatic zones (Figure 1 and Table S1). Our calculations also suggest there is between $1.4–3.5 \times 10^6$ km^2 of primary forest in blocks <500 km^2 worldwide. These smaller areas of primary forest assume particular conservation significance in otherwise extensively cleared and fragmented bioregions as refuges, core zones, reference areas and sources of propagules for landscape restoration. Almost all (98%) primary forest occurs in 25 countries with half in five developed ones (USA, Canada, Russia, Australia, and NZ) and the rest in developing countries (Figure 1 and Table S2). Only ~22% of primary forest is found in IUCN Protected Areas Categories I–VI (Table S3), which is approximately 5% of preagriculture natural forest cover. About 35% of the world's preagriculture natural forest cover (61.5×10^6 km^2) has been lost. There has been an estimated decline of 2.3×10^6 km^2 in natural forests over the past 12 years (Hansen *et al.* 2013). Globally, 0.44×10^6 km^2 of primary forest was impacted by logging and other human interventions from 2000 to 2010 (FAO 2010). This global decadal estimate of 0.4% primary forest loss, however, is likely a significant underestimate as it excluded some high forest cover nations such as Democratic Republic of the Congo where 2% of its 1.1×10^6 km^2 of primary forest was lost in this period (Zhuravleva *et al.* 2013).

Policy recommendations

Recognize primary forests as a matter of global concern within international negotiations

Deforestation and forest degradation are typically seen as a developing country problem. Primary forest protection, however, is a matter of global concern. Our analysis highlights that the distribution of primary forest, and rates of forest loss, are shared between developed and developing countries (Figure 1). Primary forest protection is also of global concern because of the role these forests play in planetary life-support systems, especially the global carbon cycle (Mackey *et al.* 2013), and in meeting international biodiversity and sustainable development goals (DellaSala *et al.* 2012). To date, attempts to negotiate an international forest treaty have failed and forests are treated in an ad hoc and uncoordinated way by relevant multilateral environmental agreements. However, significant opportunities exist for national governments to negotiate policies that promote primary forest protection through key international treaties, especially the UN Forum on Forests (UNFF), the Convention on Biological Diversity (CBD), the U.N. Framework Convention on Climate Change (UNFCCC), and the post-2015 development agenda and Sustainable Development Goals (SDGs).

A major impediment to policy emphasis on primary forests in international negotiations is the limited use made of science-based forest definitions. Since the early 1990s, there has been a move to a UN focus on "all types of forests" (including nonforest ecosystem types) to the exclusion of forests that are globally most significant ecologically or at risk. Primary forests are treated, by default,

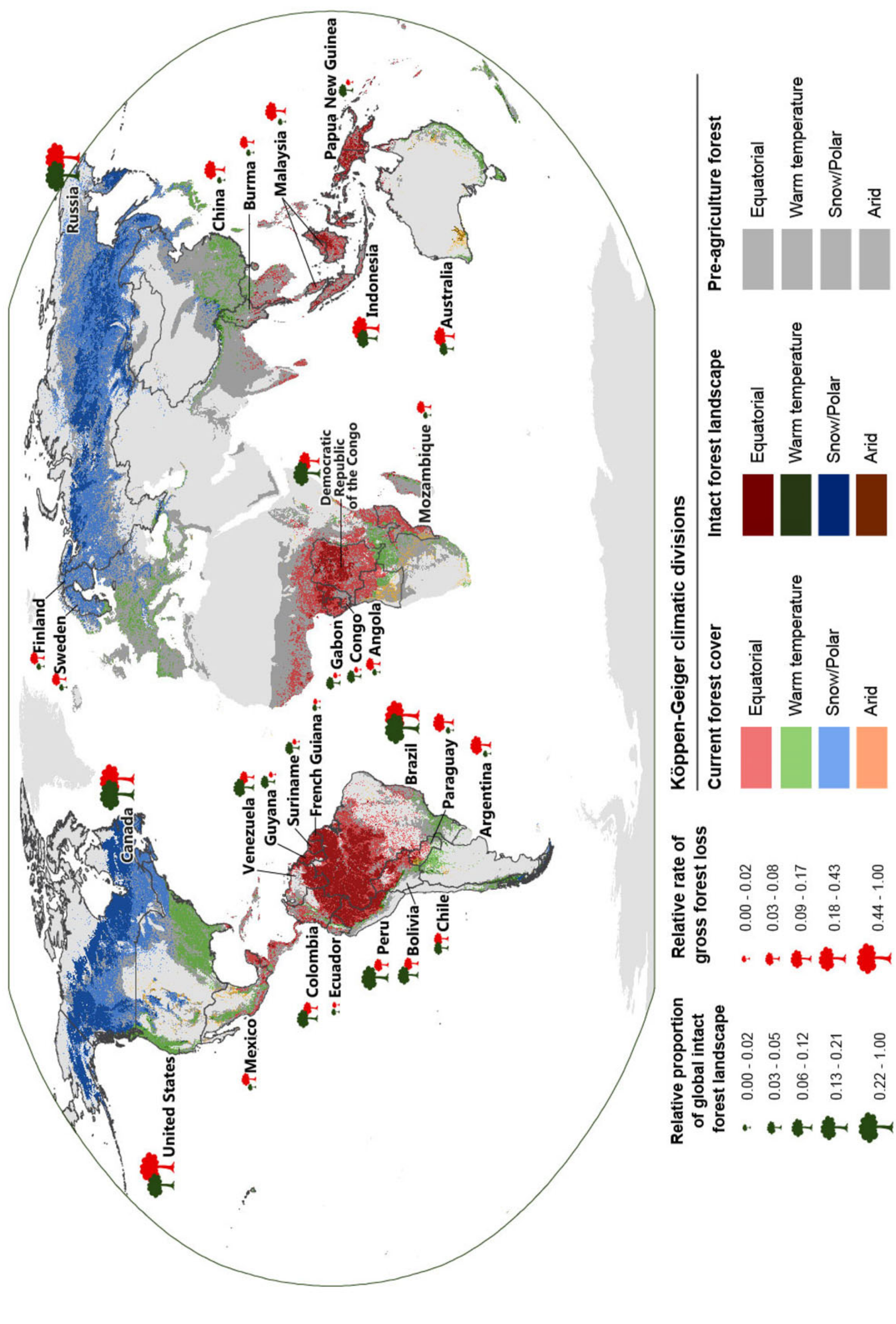

Figure 1 Distribution of forest cover within Köppen–Geigen climatic divisions: preagriculture forest; current natural forest; and Intact Forest Landscapes (IFL). The green tree icons indicate the proportion of global total IFL for the top 20 countries. The red tree icons indicate for these countries their relative proportion of total global gross forest loss (details of data sources and analyses provided in Materials and Methods, Supporting Information).

as one of many "types" of forests and are not receiving the special attention they require to maintain their unique ecological conditions and ecosystem services. This generalized and nonscience-based approach to defining forests has dominated dialogue within the UNFF and has undermined the ability of the CBD, UNFCCC, post-2015 development agenda and SDG negotiations to explicitly recognize primary forests. The UNFCCC definition of forests, for example, fails to distinguish natural forests from plantations or primary forests from production forests; degradation is not clearly defined, leading to argument over whether industrial logging is a degrading activity; and the phrase "forest conservation" is understood to equate with maintaining forest cover rather than the protection of forest biodiversity, key forest structures like large old trees (Lindenmayer *et al.* 2014), and intact ecosystems (DellaSala *et al.* 2012).

Failure by national governments and international negotiations to adopt a shared and science-based definition of forests has enabled key assumptions to go unchallenged. These include that industrial logging can conserve all forest biodiversity and ecosystem services through sustainable forest management approaches such as reduced impact logging and variable retention harvesting (Gustafsson *et al.* 2012), despite evidence to the contrary (Zimmerman & Kormos 2012). A science-based approach to forest definitions would distinguish primary from both natural forests used for industrial logging and commercially planted forests (Table S4). Other categorizations are needed. For example, there are fundamental differences in forests across major climatic zones that must be recognized (Figure 1; Supporting Information). This will provide a far more robust platform for assessing the impact of policy proposals for forest management. International policy negotiations, unfortunately, remain under the influence of the decision taken in 1992 to adopt a "whole of forest" definition. The following sections consider some of the consequences.

Incorporate primary forests into environmental accounts

Another unchallenged assumption regarding how forests are addressed within the UN system has been that primary forests have minimal economic value. Thus, the economic value of their ecosystem services are not reflected in accounting and reporting systems. Significant progress, however, is being made in the development of ecosystem-based accounting that recognizes the qualities as well as the stocks and flows of natural assets (OECD 2013). Environmental accounts at a national level should provide data that informs government decision makers about the benefits and risks of land-use policies. The significance of adopting a forest definition which explicitly includes primary forests becomes apparent here: environmental accounts can help inform policies that protect primary forest only if they recognize primary forests as a unique category of ecosystem and track their degradation and loss of intactness.

Environmental accounts can make a positive contribution to SDGs and the SDGs process has stressed the need for an ambitious and universal agenda that promotes transformational development approaches to eradicating poverty and protecting the planet's finite natural resources (UNDP & UNEP 2013). Recognizing primary forests as a distinctive class in environmental accounts would bring attention to the special contributions their ecosystem services make to SDGs including freshwater and associated watershed services. The distribution of forests and rainfall is highly correlated as photosynthesis and biomass production is a water-demanding process. The phenomenon of precipitation recycling is a well-documented positive feedback between forests and regional climate, for example, about half the precipitation in the Amazon originates from evapotranspiration (Salati *et al.* 1979). Intact forest landscapes exert a strong influence on catchment hydrology and the quality and flow of water. Forested watersheds reduce storm runoff, stabilize streambanks, shade surface water, cycle nutrients, filter pollutants, and their waters are often cooler with less sediment, nutrients, and chemicals than water from other lands (Furniss *et al.* 2010). Undisturbed forest with its understory, leaf litter and organically enriched soil is the best watershed land cover for minimizing erosion by water and any land-use activity that removes this protection increases erosion (Dudley & Stolton 2003). Intact forested watersheds therefore generally result in higher quality water than other land covers and alternative land uses such as logging which have been shown to increase sediment. Replacing old forests with young plantings often results in reduced water flow due to greater transpiration; disturbance can reduce the mean annual runoff by up to 50% compared to that of a mature forest, and can take as long as 150 years to fully recover (Jayasuriya *et al.* 1993). In a world heading to a population of nine billion people, potable and affordable water for human consumption will be an increasingly scarce and valuable resource (Dudley & Stolton 2003).

The U.N. Statistics Division's work on experimental ecosystem accounts provides the tool for national governments to begin testing and implementing systems that recognize the special ecosystem services, such as water flow and quality, arising from primary forests (OECD 2013). In implementing this approach, attention needs to be given to the quality of ecosystem stocks. In the case of primary forests, this includes tracking the impact on them of roads. As the largest human artefact on Earth (>8 × 10^6 km globally), roads are usually the first infrastructure intrusion into primary forest. Roads are typically built initially for logging, fragmenting large intact forest blocks, and leaving the fragmented habitat highly vulnerable to biodiversity loss (Gibson *et al.* 2013) Roads allow the expansion of human settlements and enable other extractive land uses, especially agriculture, mining, and ranching (Forman *et al.* 2003). There are well-established relationships between roads and land-use development which overtime lead to deforestation, unless explicit mitigation measure are put in place (Bray *et al.* 2004).

Prioritize the principle of avoided loss

Both the climate change and biodiversity problems are at crisis points. International and national policies that aim to merely slow rates of land-use-related greenhouse gas emissions and species extinctions from primary forests are inadequate as we need to be fixing these problems at a faster rate than we are causing them. There is considerable merit, therefore, in emphasizing policies that seek to avoid any further biodiversity loss and emissions from primary forest deforestation and degradation by prioritizing the principle of avoided loss.

There is now extensive scientific documentation of the unique attributes of primary forests and the contributions they make to biodiversity conservation and carbon storage and sequestration. Loss of intact forests contributes directly to the biodiversity extinction crisis. Up to 57% of tropical forest species are dependent on old-growth forest habitat, with studies on regenerating forests showing that species recovery occurs over considerably longer time scales than vegetation structural regrowth, and that reestablishment of certain species and functional group composition can take centuries or millennia (Barlow *et al.* 2007). Intact forest landscapes contain large old trees and coarse woody debris which are among the most important substrates for the maintenance of species diversity, and are particularly important in temperate and boreal forests (Lindbladh *et al.* 2013). Intact forest is therefore irreplaceable for the maintenance of native species diversity and especially those obligate forest species found only in large remnants of native forest, with forest biodiversity generally declining along a coarse gradient from old-growth forest to secondary forest, agroforestry, plantations, arable crops, and pasture (Chazdon *et al.* 2009).

Clearing and logging of primary forest results in the depletion of ecosystem carbon stocks and increased carbon dioxide emissions to the atmosphere, exacerbating the climate change problem. Current forest biomass carbon stocks are estimated at around 289 Gt C, with as much again in the other forest ecosystem pools (soil carbon and dead biomass) (FAO 2010). In total, emissions from land-use change, especially deforestation and degradation, are currently at least 10% of total annual anthropogenic emissions; comparable to emissions from the entire transportation sector (IPCC 2013). Since 1750, 33% of accumulated anthropogenic atmospheric emissions are from deforestation, degradation and other land-use changes (Houghton 2007). Primary forests store 30–70% more carbon than logged and degraded forests (Krankina & Harmon 2006; Bryan *et al.* 2010). A comprehensive approach to climate change mitigation is now needed: both fossil fuel and land carbon emissions must be curtailed. Avoiding emissions is now critical as a large fraction of anthropogenic climate change resulting from CO_2 emissions is irreversible on a multicentury to millennial time scale. Keeping forests intact is therefore a priority mitigation strategy for avoiding land carbon emissions as complete deforestation could increase atmospheric carbon dioxide concentrations by 130–290 ppm (Mackey *et al.* 2013).

The CBD and UNFCCC provide opportunities for those national governments who are signatories to advance avoided loss policies. Under the CBD, parties have agreed to a Strategic Plan for Biodiversity 2011–2020 that includes 20 Aichi Biodiversity Targets. Primary forest protection is central to achieving at least five of these targets: natural habitat loss (Target 5); terrestrial land in protected areas (Target 11); ecosystems providing essential services (Target 14); contribution of biodiversity to climate change mitigation and adaptation (Target 15); and traditional and local communities (Target 18) (CBD 2010). Primary forest protection can be used in various ways to help achieve these Aichi targets. For example, Target 11 calls for an increase in the coverage of protected areas especially Key Biodiversity Areas (KBA—places of particular importance for biodiversity) (CBD 2013). Primary forests could be explicitly evaluated under the proposed KBA Criterion C: sites that are exceptional examples of ecological integrity and naturalness as represented by their intactness and regional continuity. An indicator addressing primary forest protection could be developed to monitor progress in achieving Targets 11 and 14.

While forests are acknowledged as playing important roles in climate change mitigation and adaptation globally (CBD 2009), current provisions on forests within the UNFCCC have significant failings with respect to primary forest conservation (DellaSala *et al.* 2012). The forest policy mechanism for developed countries with binding emissions targets listed in Annex 1 of the Kyoto Protocol (KP) is called Land Use Land Use Change and Forestry (LULUCF). For non-Annex 1 countries (developing countries including Brazil, India, and China), the equivalent mechanism is called Reducing Emissions from

Deforestation and Forest Degradation (REDD+). While forests are addressed by a plethora of policies, there are significant gaps regarding primary forests, in addition to the forest definition problem noted. REDD+, for example, is being negotiated as a set of only voluntary guidelines with financial incentives that will not be tied to national emission reduction commitments. There is a serious risk that in the post-2015 agreement there will be pressure to either continue or combine LULUCF and REDD+ without addressing current limitations of either. Conversely, opening up the negotiations on forests as part of a post-2015 agreement presents opportunities to strengthen definitions, improve rules, and develop a more coherent framework that provides strong incentives to protect all primary forest.

If national governments intend to comply with the international environmental treaties they have signed, then new policies are needed that provide incentives for avoiding logging-related emissions through forest protection rather than merely reducing the rate of emissions from land use. Within UNFCCC negotiations, mitigation benefits would be maximized by strictly prioritizing forest management activities in the following order (using the terminology of Decision 1/CP.13 of the Bali Action Plan): (i) "conservation" defined as avoiding emissions by protecting primary and other natural forests; ahead of (ii) "enhancement of forest carbon stocks" defined as sequestering CO_2 by restoring degraded natural forests; ahead of (iii) "sustainable management of forests" defined in terms of reducing emissions through changed industrial logging practices. Currently, all three forest mitigation activities are recognized by REDD+ but they are poorly defined and are not prioritized. This deficiency was also noted by the European Union Parliament (2013). While this policy change may seem like a minor fine tuning, it is potentially a powerful lever that could significantly direct REDD+ investments in ways that provide incentives for national governments, local communities, and private landowners to protect primary forests. If this prioritization is not adopted, then REDD+ funds could end up doing little more than subsidizing industrial logging companies to undertake reduced impact logging/variable retention harvesting as presumed mitigation activities. Given the global distribution of primary forest, the need for international policies that direct funds and investments toward conservation actions that avoid emissions from primary forests is relevant in developed as well as developing countries.

Universal recognition of indigenous and community conserved areas

Governments could use primary forest protection as a mechanism within multilateral environmental agreements to support sustainable livelihoods for the extensive populations of forest-dwelling and dependent people, especially traditional people, in both developed and developing countries. CBD Target 18 (indigenous and local communities) would be advanced through acknowledging the contribution of primary forest protection. Within the UNFCCC, primary forest protection could be recognized as a priority ecosystem-based adaptation activity providing cost-effective, no-regret options with multiple cobenefits for humans and nature (CBD 2009). Intact ecosystems can play a vital role in maintaining and increasing resilience to climate change (Thompson et al. 2009) and in reducing climate-related risk and vulnerability (UNFCCC 2011). Ecosystem-based adaptation approaches are typically no-regret options due to the cobenefits they provide in terms of mitigation, conservation and livelihoods and because they leave open future options.

The national government negotiators at the UNFCCC could agree, like has been done through the CBD process, to recognize the special contribution of indigenous and community conserved areas to protecting primary forests and, in light of the benefits these yield for both conventions, promoting policies that invest in capacity-building with local communities living in or near forest. Local people have strong incentive to preserve the forests they depend on as the basis of traditional subsistence uses including as a source of food, shelter, and medicine. There are many examples of successful natural ecosystem protection at all scales by local communities (Nepstad 2006). Primary forest have greater resilience to external stressors compared to degraded forests, including the new additional stress of anthropogenically forced, rapid climate change (Thomspon *et al.* 2009). The Amazon, for example, has resisted previous climate changes and should adapt to future climates as well if landscapes can be managed to exclude industrial land use and maintain natural fire regimes in the majority of forest remnants (Cochrane & Barber 2009). Formal recognition of indigenous and community conserved areas in the UNFCCC negotiations could facilitate these communities' access to international climate change funds which they urgently need to provide them with the capacity and resources to protect primary forests.

Conclusions

International environmental negotiations are failing to halt the loss of the world's most important primary forests. While multiple stressors are at play in deforestation and degradation, and many nongovernment actors have important roles to play (Nepstad *et al.* 2014), national governments can help reset forest policies globally by shifting away from addressing "all types of forests" generically toward a new regime based on the key principle that protection of primary forests is prioritized and accelerated. Enabling this shift also will require strengthening global policy coordination in support of primary forest protection across multilateral environmental agreements and UN processes, such as the UNFF, SDGs and the post-2015 development agenda. This will enhance synergies, strengthen cross-treaty linkages, avoid conflicting decisions, and help to develop appropriate financial mechanisms and responses in national action plans and programs.

The biodiversity impacts of industrial logging are chronically problematic in all forest biomes—tropical, (Zimmerman & Kormos 2012), boreal (Schmiegelow *et al.* 2006), and temperate (Lindenmayer *et al.* 2011)—with immediate, lagged, and cascading impacts. Complementary policies are needed that reduce pressure to open up primary forest for wood production and other intensive land uses by (a) shifting expansion of agricultural commodity production entirely out of primary forests to previously cleared land and (b) promoting restoration of degraded forest land. The 23×10^6 km^2 of secondary forest (i.e., those subject to industrial logging or designated for multiple uses including wood production) provide vast areas of habitat for many species and ecosystem services (Putz *et al.* 2008) (albeit in a limited way relative to primary forests; van Bruegel *et al.* 2013). In addition to the mitigation benefits noted from avoided emissions, the potential contribution of forest restoration to reducing atmospheric carbon dioxide concentrations is significant (40–70 ppm if all cleared land was restored) (House *et al.* 2002). Secondary forests can serve as buffers and connections for primary forests and are important to landscape-wide conservation efforts (Crooks & Sanjayan 2006). Comprehensive forest protection is best achieved when both large and small blocks of primary forests are embedded within efforts to conserve and restore secondary forests more generally. Where forest is subject to industrial logging, therefore, changing logging practices and regimes so that they have lower emissions and biodiversity losses, and preventing management failures, are important components of a comprehensive landscape-level approach to forest conservation. However, we caution against subsidizing industrial logging operations to mitigate their environmental impacts as there is no substitute for the unique biodiversity values and ecosystem services that primary forests provide.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Text S1: Materials and Methods

Text S2: Additional material on forest definitions

Table S1: The area of intact forest landscape (IFL) in the main climatic zones of Köppen–Geiger

Table S2: The top 25 countries ranked by their area of intact forest landscape

Table S3: The area of intact forest landscape (IFL) in IUCN Protected Areas Categories I–VI; the area and percentage of protected IFL

Table S4: General ecological attributes of primary forests, natural forest with industrial logging, and plantation forests for major forest types as stratified by climatic zones as defined in Methods and Materials

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Supporting Information

Contents

Text S1: Materials and Methods

The data for Fig. 1 came from the following sources and analyses.

(i) The background map layer of extant natural forest cover is sourced from a global land cover map (Arino *et al.* 2009). This global land cover layer was derived from NASA MODIS satellite data and has 23 land-cover classes. We reclassified the forest cover layer by two classes, namely, forest and non-forest. We selected the classes that described a type of forest, namely: 40 - Closed to open broadleaved evergreen or semi-deciduous forest; 50 - Closed broadleaved deciduous forest; 60 - Open broadleaved deciduous forest; 70 - Closed needleleaved evergreen forest; 90 - Open needleleaved deciduous or evergreen forest; 100 - Closed to open mixed broadleaved and needleleaved forest; 110 - Mosaic Forest-Shrubland/Grassland; 120 - Mosaic Grassland/Forest-Shrubland; 160 - Closed to open broadleaved forest regularly flooded (fresh-brackish water); 170 - Closed broadleaved forest permanently flooded (saline-brackish water).

(ii) The map layer of intact forest landscapes (IFL) was sourced from a global survey published by Potapov *et al.* (2008) based on remotely sensed and GIS data sources using the following parameters: forest canopy cover > 20%; minimum forest patch sizes of 4 km^2; minimum forest zone of 500 km^2 (50,000 ha); and minimum patch width of 10 km. Note that IFL can contain non-forest areas, perhaps up to 15%, which results in uncertainty when using these data in conjunction with other data sources.

(iii) Forests were analysed and are colour labelled in the figure according to a spatial model of the major climatic divisions of the Köppen-Geiger classification (Kottek *et al.* 2006). We intersected the global map of intact forest landscapes with this climatic model (Table S1). The GIS calculation was implemented in ArcGIS desktop 10.1. In lieu of transforming the datasets to calculate area, the spatial layers were kept in a geographical projection (WGS84) and the area of the polygons was calculated using the spherical coordinates with the “geosphere” (Hijmans *et al.* 2012) package of the statistical computing software R 2.15.2 (R Core Team).

(iv) We calculated the area of IFL per country and identified the top 25 countries ranked by this statistic (only the top 20 are mapped due to cartographic limitations) (Table S2).

(v) The data for the International Union for Conservation of Nature (IUCN) protected areas were sourced from the World Database on Protected Areas (WDPA) (IUCN-UNEP 2013). The shapefile contains a comprehensive global database on terrestrial and marine protected areas. We intersected the terrestrial protected areas that were assigned one of IUCN's six recognized categories of protected areas (referred to as IUCN Protected Area Categories I-VI) with the global map of IFL (Table S3).

(vi) National level statistics for recent gross forest loss were sourced from a global remote sensing based survey (Hansen *et al.* 2013). We identified the top 25 countries with the highest rates of gross deforestation for illustration in Figure 1 (Table S3). We used gross rather than net deforestation because net includes forest regrowth. The published figures did not enable us to distinguish what proportion of gross was from primary or natural forest that was degraded by logging and other land use intrusions. Therefore, this gross deforestation statistic is used in Figure 1 as a simple indicator of countries where forests are most at risk.

(vii) Our estimate of primary forest in blocks <500 km^2 was made by comparison of IFL data with statistics compiled by the Food and Agriculture Organisation (FAO 2010a, b). These data were compiled from national reports and therefore there are gaps and discrepancies arising from some high forest cover countries failing to report any forest statistics from differing forest classification systems and interpretations of guidelines. The estimate of pre-agricultural global forest cover came from a history data base of the global environment called HYDE (Goldewijk 2001).

Table S1

The area of intact forest landscape (IFL) in the main climatic zones of Köppen-Geiger. The fraction of total (%) is the percentage of IFL in each climatic zone as a fraction of the total area of IFL. The FAO area of primary forest is compiled from national reports (FAO 2010a, b).

Climatic zone	**Area (km^2)**	**Area (ha)**	**Fraction of total (%)**
Equatorial	6 034 545	603454574	46
Arid	101 935	10193525.33	1
Warm Temperature	383 170	38317000.73	3
Snow	6 149 700	614970088.4	47
Polar	357 227	35722776.68	3
Total Area	13 026 579	1 302 657 965	100
FAO area of primary forest	13 588 640	1 358 864 000	
FAO primary forest not IFL >50 000 ha^{-1}	562 060	56 206 034	

Table S2 The top 25 countries ranked by their area of intact forest landscape.

IFL ranking	Name	km^2
1	Canada	3,096,632
2	Russia	2,736,141
3	Brazil	2,494,760
4	D. R. of the Congo	647,275
5	United States	587,394
6	Peru	570,594
7	Indonesia	370,780
8	Colombia	354,443
9	Venezuela	315,995
10	Bolivia	230,101
11	Papua New Guinea	163,812
12	Guyana	145,618
13	Congo	140,799
14	Australia	138,761
15	Chile	110,097
16	Gabon	109,197
17	Suriname	108,733
18	French Guiana	66,352
19	Burma	53,536
20	Ecuador	53,467
21	Cameroon	53,266
22	China	51,138
23	Paraguay	45,256
24	New Zealand	42,963

25	Argentina	39,231

Table S3

The area of intact forest landscape (IFL) in IUCN Protected Areas Categories I-VI; the area and percentage of protected IFL.

IUCN terrestrial protected area category	Area (km^2)	Fraction of total IFL(%)
Ia	254 412	9
Ib	246 223	9
II	1 047 860	37
III	59 660	2
IV	309 235	11
V	163 711	6
VI	758 956	27
Total area of IFL found within IUCN Protected Area Categories I-VI	2 840 057	
Total global area of IFL	13 100 000	
Percentage of PIFL found within IUCN Protected Areas Categories I-VI	22%	

Text S2: Additional material on forest definitions

Our use of the term 'primary forests' is designed to focus attention on a subset of global forests possessing particular characteristics. Here, we explain the scientific basis to our selection of this term and further explain its meaning and significance.

Forests can be defined using various criteria, including: vertical structure of vegetation cover at a stand level (canopy height and density, number of vertical layers); taxonomic composition of the dominant canopy species; degree of autopoiesis (i.e., self-establishment and regeneration); forest productivity as measured by site index; gross level of timber stand volume; age of the dominant tree and shrub species; geographic location; climatic domains; and condition as impacted by land use and human perturbation. Over 800 definitions of forests and wooded areas have been identified globally (Lund 2014).

Fundamental ecological differences, however, are found in the natural characteristics of primary forests along major climatic zones (e.g., tropical, temperate, boreal). Structurally, the term 'forest' is typically defined as vegetation which at ecological maturity has a canopy density and height above a minimum threshold (e.g., >30% and >20m). This level of biomass production requires substantial and sustained rates of photosynthesis and therefore forests are typically found where the ratio of actual evapotranspiration to equilibrium evapotranspiration assessed over the full year is generally ≥0.45 but for evergreen forests is ≥0.65 (Prentice *et al.* 1992). At a global scale, therefore, all forests occur where it is climatically relatively wet (or at least sufficiently wet seasonally) and they are primarily differentiated by thermal gradients (but also by rainfall seasonality); hence the distinction commonly made between tropical, subtropical, temperate and boreal forests. As thermal gradients (along with rainfall seasonality) have been significant exogenous selective forces on the evolution of forest biota, the major climatic zones also distinguish genetically distinctive forest taxa.

The term ‘primary’ is used to also refer to both (i) natural forests largely undisturbed by industrial-scale land use and (ii) natural forests that have reached ecological maturity. In many forest ecosystems, species with specialized life history traits occupy different successional stages in the development of a stand following disturbance or the death of canopy trees. Typically, fast growing and shorter-lived tree species dominate disturbed sites, followed by slowing growing longer-lived ones (Chazdon *et al.* 2010). Terms such as ‘unlogged,’ ‘undisturbed,’ ‘intact,’ ‘natural,’ ‘frontier,’ ‘ancient,’ ‘virgin,’ and ‘old growth’ have been used interchangeably with primary. ‘Old-growth’ is a commonly used term, though there is no generally agreed definition because it varies regionally and locally. It is typically defined as a forest with trees older than 120 years; however, trees with a lifespan of <120 years old can dominate some older forests. It is also possible for disturbed/secondary forests to retain old-growth structural and functional characteristics as biological legacies. The structural characteristics of old growth can vary between locality/forest type but typically include mature trees (some very old), standing dead trees and downed logs, abundant coarse woody debris, and vertical and horizontal complexity in vegetation layering.

The Convention on Biological Diversity, following from the FAO (2010a, b) definition of forest, defines primary forest as forest that has never been logged and has developed following natural disturbances and under natural processes, regardless of its age (CBD 2009). It also includes here forests that are used inconsequentially by indigenous and local communities living traditional lifestyles relevant for the conservation and sustainable use of biological diversity.

The U.N. Environment Program World Conservation Monitoring Centre and the Centre for International Forestry Research generally refer to forests by broad ecosystem type (e.g., mangrove, lowland evergreen broadleaf rainforest). While they do not use the term primary forest, ‘disturbed natural forest’ is defined as any non-plantation forest that has in its interior significant areas of disturbance by people, including clearing, felling for wood extraction, anthropogenic fires, and road construction, for example. All forests, regardless of their human footprint, are defined as having > 30% canopy cover (UNEP-WCMC 2009) *(38)*.

The issue of spatial scale is critical in defining, mapping and accounting for forest condition. Most field based forest observations are at the stand-level ($\leq$1ha^{-1}). Industrial logging operations are based on logging schedules that operate at the stand-level with a ‘forest’ consisting of a mosaic of managed stands at the landscape scale. This industrial focus on stand-level has influenced the definition of forests in various international processes, including: (i) the FAO (2010a, b), with the definition of a forest as comprising a 5 ha^{-1} minimum forest area, 5 m minimum tree height and 10 % minimum crown cover; and (ii) the UNFCCC, which while allowing individual national definitions requires they conform to threshold values (0.01 – 1.0 ha^{-1} minimum area; 2.5 m minimum tree height; 10-30 % crown cover; 40 % minimum crown cover threshold for closed forest).

Consistent with the principles of ecological hierarchy theory, the sampling resolution and geographic extent of a study area determine the patterns that are recognized broadly and specifically as an intact forest. At a site-scale ($\leq$ 1ha^{-1}), intactness is a function of vegetation structure (canopy height and cover, number of vertical layers). Under natural conditions, primary forests at the landscape scale (~1.0 x 10^{4} ha^{-1}) will encompass a mosaic of successional stages and ecosystem types. For this reason, an ecological perspective demands consideration of the intactness of forests at the landscape- rather than stand-level. The stand-level alone, therefore, does not adequately encompass important forest ecosystem features and qualities that vary more broadly over larger areas. The landscape-level (>1 ha^{-1} to ~ 50,000 ha^{-1}) better captures the multi-scale processes and patterns that characterize forest ecosystems – hence the term ‘forest landscapes.’

‘Intactness’ is a landscape-level metric that quantifies the extent to which a natural forest landscape has been degraded and fragmented by land use impacts, including roads and development. An intact forest landscape (IFL) is defined here as an unbroken expanse of natural ecosystems within the zone of current forest extent, showing no signs of significant human activity, and large enough that all native biodiversity, including viable populations of wide-ranging species, could be maintained (Potapov *et al.* 2008). Although all IFL are within the forest zone, some may contain extensive naturally treeless areas, including grasslands, wetlands, lakes, alpine areas, taiga, and ice. In general, intact forest landscapes have the following characteristics: primarily forested; large enough to support viable populations of all species associated with that forest type even in the face of natural disturbances of a magnitude to occur once in a century; dominated by native tree species; home to most of their evolved, characteristic biodiversity; structure and composition determined mainly by natural events; relatively unmanaged by humans, notwithstanding long standing interactions with indigenous forest people; and, in forests where patches of trees of different ages occur naturally, a heterogeneous landscape. In sum, primary forests retain their full complement of evolved characteristic biodiversity, adaptive capacities, optimized ecosystem processes and bio-cultural relationships.

The ecological and conservation significance of a given intactness threshold value varies with climatic zone and landscape context. The 500 km^2 threshold value is appropriate for a reconnaissance assessment and it is likely ecologically significant for many snow/polar (boreal) forest landscapes given the typically large spatial scale of natural disturbance regimes. The temperate forest zone has only about 3% of the world's primary forest reflecting the extent to which these forest have been cleared and logged. For example, in the Australian state of Victoria, there is < 1.2% of old growth mountain ash forest (dominated by *Euclayptus regnans*) left after logging, fires, and the combination of the two (Lindenmayer *et al.* 2012). Here, a lower threshold is warranted as, among other things, the remnants play a vital role as source habitats, restoration benchmarks, and core zones in multi-tenure protected area networks. The same is true for the Pacific Northwest where approximately 20% of forests >150 years old remain due to extensive logging (Strittholt *et al.* 2006).

The move towards international forest deliberations focusing on "all types of forests" can be traced to the 1992 Rio Earth Summit (UN 1992). This more generalized approach included vegetation types that structurally in science-based classification schemes are considered non-forest ecosystem types such as woodlands. As a result, this has led global attention away from forests that are globally of most ecological significant or at risk, including primary forest.

Table S4

General ecological attributes of primary forests, natural forest with industrial logging, and plantation forests for major forest types as stratified by climatic zones as defined in Methods and Materials: equatorial (more commonly referred to as "tropical"); snow/polar ("boreal"); and warm temperate ("temperate" including what in some regions are known as "cool temperate"). The attributes of natural forests with industrial logging will vary depending on the kind of forest management applied.

Ecological Attribute	**Primary forest**	**Natural Forests With Industrial Logging**	**Plantation**
Genetic diversity including intra-species diversity	Moderate (snow/polar) to exceptional (equatorial)	Reduced due to selective logging of largest most commercially valuable trees	Very low with commercially manipulated genomes to grow under site-specific conditions
Alpha diversity	Low (snow/polar) to exceptional (equatorial)	Reduced depending on level of logging and associated impacts	Very low
Narrow range endemics	Low (snow/polar) to exceptional (equatorial)	Low due to loss of habitat specialists	Very low
Food web dynamics	Fully functional predator-prey dynamics; large carnivores all present	Few large carnivores	Low to none
Pollination	Low (snow/polar) to exceptional (equatorial)	Reduced depending on degree of biomass removals (especially flowering plants)	Low to none

Total carbon storage and sequestration	Exceptional organic carbon stocks in all types (equatorial, snow/polar, warm temperate) but sequestration rates greatest in equatorial	Significant CO_2 emissions from depletion of living and dead biomass carbon and soil carbon stocks with magnitude depending on logging intensity and method	Long-term CO_2 emissions (decades to centuries) depending on removal of original biomass
Micorhizzal relations and soil microfauna	Low (boreal, tropics) to exceptional (temperate)	Soils compacted, biota reduced	Soils erosive, biota reduced especially below ground, invasives may dominate without control
Hydrological cycles	Intact and functional	Altered	Highly altered water quality and quantity especially by roads
Natural disturbance regimes	Intact and functional operating across full range of spatio-temporal scales	Altered at site and landscape level – e.g., fire regimes may be suppressed or magnified	Highly altered – e.g., maybe suppressed or magnified
Stand structure	Relatively simple (snow/polar) to moderate-exceptional (equatorial, warm temperate)	Greatly simplified depending on extent of removal of old trees and coarse woody debris	Extensive loss of old trees, biological legacies, oversimplified
Seral stages	Complex, all stages represented, especially	Loss of ecologically mature stages, salvage logging of	Young trees with simplified composition

	old growth	disturbed areas limits complex early seral stage from developing	and structure only, no complex early seral stage due to commercial logging
Landscape heterogeneity	Large undisturbed patches intermixed within a mosaic of seral stages depending on natural disturbance events, resulting in high beta diversity	Low to moderate depending on extensiveness and intensiveness of logging and degree of remaining patch diversity	Uniform and low
Landscape connectivity	Natural connections intact	Fragmented with little interior habitat and moderate edge penetrance	Highly fragmented with mostly edge conditions
Adaptation potential to climate change	High due to low land-use stressors, intact processes, favourable microclimates that may provide refugia, and native species diversity that may infer resistance	Reduced due to land-use stressors, diminished biodiversity, and altered microclimates	Low due to high land-use stressors, highly altered microclimates, and invasive species intrusions
Human footprint (infrastructure, invasives etc.)	Low (if left undisturbed)	Moderate to high depending on forest management practices	High to exceptional

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