A Global Evaluation of Forest Interior Area Dynamics

Using Tree Cover Data from 2000 to 2012

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Abstract

Context. Published maps of global tree cover derived from Landsat data have indicated substantial changes in forest area from 2000 to 2012. However, the changes can be arranged in different patterns, with different consequences for forest fragmentation. Thus, the changes in forest area do not necessarily equate to changes in forest capacity to sustain landscape ecological services.

Objective. The objective is to assess global and regional changes in forest fragmentation in relation to the change of forest area from 2000 to 2012.

Methods. Using published global tree cover data, forest and forest interior areas were mapped in 2000 and 2012. The locations of forest interior change were compared to the locations of overall forest change to identify the direct (pixel level) and indirect (landscape level) components of forest interior change. The changes of forest interior area were compared to the changes of total forest area in each of 768 ecological regions.

Results. A 1.71 million km^2 (3.2%) net loss of global forest area translated to a net loss of 3.76 million km^2 (9.9%) of forest interior area. The difference in loss rates was consistent in most of the 768 ecological regions. The indirect component accounted for 2.44 million km^2 of the net forest interior change, compared to 1.32 million km^2 that was attributable to the direct component.

Conclusion. Forest area loss alone from 2000 to 2012 underestimates ecological risks from forest fragmentation. In addition to the direct loss of forest, there was a widespread shift of the remaining global forest to a more fragmented condition.

Keywords. Spatial analysis; forest fragmentation; monitoring; assessment; ecosystem services

Introduction

Forest loss and degradation threaten the maintenance of ecological services in forested landscapes (Millennium Ecosystem Assessment 2005). Global monitoring tends to focus on total forest area (e.g., FAO 2010) but assessments are imprecise when they combine country-level data (Mather 2005). An abundance of satellite imagery has created opportunities to improve forest inventory and conservation of forest resources (Asner, 2014; Rose et al 2014). The publication of the Landsat archive by the U.S. Geological Survey and the National Aeronautics and Space Administration has stimulated a variety of efforts to map forest extent and change (Loveland and Dwyer 2012; Wulder et al 2012; Roy et al 2014). For example, Sexton et al (2013) produced a global forest map at the native 30 m x 30 m (0.09 ha) spatial resolution of the Landsat data. Remotely sensed data also provide a synoptic perspective needed to monitor forest consistently through time (Innes and Koch 1998; Pelletier and Goetz 2015). From a global analysis of the Landsat data to map tree cover, disturbance, and recovery, Hansen et al (2013) reported a gross forest loss of 2.29 million km^2 from 2000 to 2012.

Does the reported decrease of global forest area equate to increased risk of ecological impacts? The answer is probably no, because forest area alone is an incomplete indicator of the capacity of forests to sustain ecological services (Chazdon 2008). The spatial pattern of forest is important because the same area of forest can be arranged in different ways on the landscape with important consequences for ecosystem processes (Harris 1984; Andrén 1994; Pickett and Cadenasso 1995; Fahrig 2003). Similarly, forest area loss is an incomplete indicator of ecosystem changes because the loss can occur in different patterns. Furthermore, gross forest loss may overestimate impacts because forest can be gained as well as lost from a landscape

(Kurz 2010). Analysis of forest fragmentation has to account for the patterns of the forest losses and gains in relation to the extant forest patterns (Wickham et al 2007, 2008).

In this study, we analyzed global changes in forest fragmentation from 2000 to 2012 by mapping the changes in forest interior area that were associated with the forest gains and losses identified by Hansen et al (2013). Forest interior area is an ecologically relevant indicator of fragmentation because most natural forests cover large areas such that the natural state of most forest area is interior. Forest area that is not interior is at greater risk from "edge effects" that range from higher rates of invasive species and atmospheric pollutant deposition to less mesic microclimates (Kapos 1989; Robinson et al 1995; Murcia 1995; Keddy and Drummond 1996; Laurance et al 1998; Gascon et al 2000; Cadenasso and Pickett 2001; Weathers et al 2001; Ries et al 2004; Laurance 2008). Single-date analyses of forest fragmentation have been conducted globally at 1 km^2 resolution (Riitters et al 2000) and 0.09 ha resolution (Haddad et al 2015). The new forest maps permit a novel analysis of temporal changes in global forest fragmentation, including evaluation of the regional relationships between total forest change and forest interior change. Our objectives were to map the relatively unfragmented forest, to quantify its rate of loss in different regions, and to identify regions with high rates of loss per unit change of forest area.

Forest interior is a contextual attribute in the sense that a forest pixel is interior (or not interior) because of the landscape context surrounding that pixel. Spatial analysis of the new forest maps is required because edge influences can extend hundreds of meters from forest edge (Murcia 1995; Laurance 2000; Ries et al 2004), making it unlikely that an isolated 0.09 ha forest parcel will experience real forest interior conditions. One approach to mapping forest interior is to label a given forest pixel as interior (or not interior) based on the proportion of its unique surrounding landscape that is forest (Riitters et al 1997). The resulting forest interior map is the subset of the forest map which meets a defined threshold proportion. This approach is computationally equivalent to a definition of forest interior based on minimum distance to edge when the threshold value is 1, and it reduces the influence of isolated and small forest changes when the threshold value is less than 1 (Riitters et al 2002).

As the forest map changes over time, the patterns of forest gains and losses cause direct and indirect changes of forest interior area. Direct change refers to the gain or loss of a forest pixel that is itself interior. Indirect change occurs where forest gains or losses near a persistent forest pixel cause the landscape proportion of forest to cross the threshold criterion for that forest pixel. The direct and indirect components of forest interior change are identified by combining maps of forest change and forest interior change. To illustrate the conceptual approach, consider a definition of forest interior as a forest pixel that is not forest edge (Figure 1). Where forest is lost or gained in small patches, there are no direct or indirect changes of forest interior. Where forest changes occur at the edge of large patches, there are no direct changes of forest interior but there are indirect changes because the distance to edge has changed for some of the original forest. Where forest loss perforates a large patch, the perforation is a direct loss of forest interior and the edge that is created by the perforation is an indirect loss. Similarly, where forest gain removes a perforation, there are direct and indirect gains of forest interior. We employed this conceptual model except with a different criterion to define forest interior.

#Figure 1 approximately here#

Methods

Forest cover in 2000 and 2012

We used the Global Forest Change Database (GFCD: Hansen et al 2013), obtained from Google Earth Engine (http://earthenginepartners.appspot.com/science-2013-global-forest) as a set of 10 degree x 10 degree map tiles in a geographic projection; each tile was 36,000 pixels x 36,000 pixels. The data were projected to an equal-area geographic projection to ensure that the neighborhoods used in later analyses were the same size everywhere. To accomplish that, subsets of map tiles were mosaicked into units approximating continents and then projected to a Lambert azimuthal equal-area projection optimized for each continent. The target pixel area was 0.09 ha for consistency with the native resolution of the original Landsat data. That procedure was followed for each of four maps from the GFCD: (1) tree canopy cover in the year 2000, defined as percent canopy closure for all vegetation taller than 5 m in height; (2) forest loss during the period 2000–2012, a binary indicator defined as a change from non-zero to zero tree cover percent; (3) forest gain during the period 2000–2012, defined as the inverse of forest loss, and; (4) data mask, from which "mapped land surface" defined the study area, and "no data" and "permanent water body" were treated as missing data and ignored when identifying forest interior area.

We defined forest in 2000 as a pixel with non-zero tree cover percent. Since the GFCD does not include a map of tree cover in 2012, we constructed a 2012 forest map by evaluating pixel transitions to and from a non-zero tree cover state from 2000 through 2012 (Table 1). It was possible for a given pixel to be encoded as both forest gain and forest loss because the GFCD includes annual information about forest loss. Gross forest gains and losses over the entire time interval were defined by the per-pixel differences between the derived forest maps in 2000 and 2012. These definitions of forest gain and loss are based on tree cover percent in 2000 and modeled tree cover percent in 2012 (Table 1), which may differ from the definitions of forest cover gain and loss in Hansen et al (2013).

#Table 1 approximately here#

Forest interior analysis

We mapped forest interior area by using a “moving window” analysis (Riitters et al 1997) of the forest cover maps for 2000 and 2012. This approach was used in previous global analyses of forest fragmentation using land cover maps with 1 km^2 resolution (e.g., Riitters et al 2000; Wade et al 2003), and national analyses using land cover maps with 0.09 ha resolution (Riitters et al 2002; Riitters and Wickham, 2012). The approach has also been used with 0.09 ha resolution forest maps in several national assessments (USDA Forest Service 2004, 2011, 2012; Heinz Center 2008; US Environmental Protection Agency 2008).

At each date, each pixel was described by its forest area density (FAD), defined as the proportion of a surrounding 33 pixels X 33 pixels (0.9801 km^2) window that was forest. Hereafter, we refer to that window as a 1 km^2 neighborhood. Individual forest pixels at each date were then labeled as forest interior if their associated FAD at that date was ≥ 0.9 (McIntyre and Hobbs 1999). At each date, the map of forest interior comprised the subset of all extant forest pixels which met the criterion of FAD ≥ 0.9. The maps of FAD in 2000 and 2012 were then intersected, pixel by pixel, with the maps of forest, forest gain, and forest loss.

Net changes in forest interior area between the two dates were either direct, meaning they were attributable to the gain or loss of a forest pixel that was itself interior, or indirect, meaning they were attributable to the forest gains and losses in the neighborhood of a persistent forest pixel. We estimated the direct component of forest interior change by evaluating forest losses in relation to FAD in 2000, and forest gains in relation to FAD in 2012. The indirect component of forest interior change was estimated by evaluating net changes in the forest interior status of all pixels that were forest at both dates. The forest interior status of a given forest pixel changed indirectly if net forest gain in the neighborhood increased the FAD value to ≥ 0.9, or if net forest loss decreased the FAD value to < 0.9.

We compared the regional changes in total forest area with changes in forest interior area by elasticity, calculated as net percent change in forest interior area divided by net percent change in total forest area within a given geographic region. Regional summaries were prepared using maps (World Wildlife Fund 2004) of 14 terrestrial biomes and 768 terrestrial ecological regions described by Olson et al (2001). We labeled six of the 14 biomes as "forest" biomes based on our expectation that the original land cover in those biomes was dominated by forest. The non-forest biomes were included because they contain a substantial share of the global tree-covered area (Hansen et al 2013). We excluded the Oceanic and Antarctic biomes, ecological regions that were outside the area of the tiles retrieved from the GFCD, uninteresting ecological regions such as "rock and ice," and the small ecological regions that were not represented after overlaying the GFCD.

In a moving window analysis, the measurement scale is defined by the choices of window size and threshold FAD value. We used a single measurement scale in order to focus on temporal changes in forest interior area in relation to changes in total forest area, and the geography of that relationship. We selected the measurement scale based on our experience conducting multi-scale moving window analyses using forest maps with various spatial resolutions nationally and globally. The use of different window sizes or threshold FAD values would naturally change the absolute amount of forest interior area at each date, which would change the magnitude (but not the sign) of elasticity, but it would not significantly change the geography of the relationships between total forest change and forest interior change (Riitters and Wickham 2012).

Although we used a consistent method globally, global aggregate results are difficult to interpret because they obscure which types of forest are lost or gained. For example, the loss of tropical forest is arguably not offset by a gain of temperate woodland. Those differences are unimportant at the measurement scale we used to identify forest interior because large differences in forest types do not typically occur at that scale. To account for large differences in forest types over larger geographic extents, we summarized changes within ecological regions and biomes (Olson et al 2001). In this way, our approach provided a globally-consistent protocol to identify forest interior while providing regional scale information about forest interior trends in relation to total forest area trends.

Results

Global

Global changes in forest and forest interior area are summarized in Table 2. The forest interior area in 2000 was 37.79 million km^2, representing 71% of all forest area. Between 2000 and 2012, the gross gains and losses of all forest area were 0.35 million km^2 and 2.06 million km^2, respectively, resulting in a net loss of 1.71 million km^2 or 3.2% of all forest area. In comparison, 0.48 million km^2 and 4.24 million km^2 of forest interior area was gained and lost, respectively. The result was a net loss of 3.76 million km^2 or 9.9% of forest interior area between 2000 and 2012, when 66% of the remaining forest area was interior. The global net rate of forest interior area loss was 3.1 times the global net rate of all forest area loss, and the net loss of forest interior area was more than twice the net loss of all forest area.

#Table 2 approximately here#

The net direct component of forest interior change (conversions between forest interior and non-forest) accounted for approximately one-third of the global net loss of forest interior area (Table 2). That occurred because total forest loss tended to follow the distribution of total forest in relation to FAD in 2000, but the difference between forest loss and forest gain increased with increasing FAD (Figure 2). For FAD ≥ 0.9 the difference between the gains and losses is the net direct component of forest interior change. The remaining two-thirds of forest interior area loss came from the indirect component of change whereby pixels that were forest in both 2000 and 2012 exhibited a change of interior status due to net forest loss or gain in their neighborhood. Among the 14 terrestrial biomes, the elasticity values indicate the rate of forest interior loss was between 2.5 and 6.7 times larger than the rate of total forest loss (Table 3).

#Figure 2 approximately here#

Forest biomes

Tree cover dynamics in the six forested biomes accounted for 80% and 82%, respectively, of the global net losses of all forest area and forest interior area (Table 3). The loss of interior area was between 10% and 17% of area in 2000 on a per-biome basis, with the largest percentage loss in the Temperate Coniferous Forests biome. The largest area loss, representing approximately half of the total loss of interior area in forest biomes, occurred in the Tropical & Subtropical Moist Broadleaf Forests biome which contained approximately half of the total interior area. Compared to a forest biome average direct loss rate (35%), the Boreal Forests & Taiga biome had the highest rate (46%) and the Tropical & Subtropical Coniferous Forests biome had the lowest rate (19%). Elasticity was approximately twice the forest biome average value (3.1) in the Tropical &

Subtropical Coniferous Forests biome (6.7) and Temperate Broadleaf & Mixed Forests biome (5.9).

#Table 3 approximately here#

Non-forest biomes

The non-forest biomes together accounted for 18% of the global loss of forest interior area (Table 3). Two-thirds of that loss was in the Tropical & Subtropical Grasslands, Savannas & Shrublands biome, which lost 6% of the forest interior area in 2000. While forest dynamics in the other seven non-forest biomes had relatively little influence on aggregated global area statistics, elasticity was higher than the global elasticity in six of them, and the rate of forest interior loss exceeded 10% in four of them – the Mangroves (11%), Temperate Grasslands, Savannas & Shrublands (12%), Deserts & Xeric Shrublands (13%), and Mediterranean Forests, Woodlands & Scrub (19%) biomes.

Ecological regions

Of the 768 ecological regions included in this analysis, 434 were in the six forest biomes. Among those 434 regions, the median net losses of all forest area, and forest interior area were 1.9% and 8.0%, respectively. There were net gains of forest in 11 of those regions, including the only three regions that exhibited net gains of forest interior area. Within the 334 ecological regions in the non-forest biomes, the corresponding median loss values were 1.4% and 6.8%, respectively. Net gains of forest area occurred in 30 of those regions, including the only three regions in non-forest biomes with net gains of forest interior area. Figure 3 illustrates the ecological region changes in forest area and forest interior area, along with inset maps identifying forest biomes and regional forest area percent in 2000. With few exceptions, the rates of forest interior loss exceeded rates of all forest loss, especially in forest biomes. Net gains of forest area and forest interior area occurred primarily in non-forest biomes and in ecological regions with small forest cover percentages in 2000. Several ecological regions exhibited net gains of forest area but not forest interior area.

#Figure 3 approximately here#

Discussion

Sustaining forest interior is arguably as important as sustaining forest itself (Chazdon 2008). Our analysis indicated that total forest area change is not necessarily a good predictor of forest fragmentation change. Forest interior area was lost at a greater rate than non-interior forest area across all biomes (Table 3) and in most terrestrial ecological regions (Figure 3). Furthermore, the substantial regional variation in elasticity indicates that a given amount of forest loss can result in substantially different impacts on fragmentation. Direct conversion of forest interior area to non-forest area accounted for approximately one-third of the forest interior area that was lost (Table 3). Natural disturbances such as wildfire and insect damage are very likely to be the primary driver of tree cover changes in boreal, mountainous, and arid ecological regions; anthropogenic factors are less likely to be drivers in those regions because they are not dominated by agriculture or human occupation. Where human activities are dominant, land use is typically the primary driver of forest change (Turner et al 2007). Hosonuma et al (2012) found that three-fourths of recent deforestation in developing tropical and subtropical countries was due to conversion to agricultural land use. Conversion to urban and infrastructure uses are more common in developed countries.

This analysis can inform different types of concerns about the loss of forest interior area. For example, conservation of total forest interior area might focus on the Tropical & Subtropical Moist Broadleaf Forests biome because it contained 35% of the global total in 2000 and accounted for 38% of global loss. The Tropical & Subtropical Grasslands, Savannas & Shrublands biome contained the second largest share (24%) of the global total in 2000, but accounted for only 13% of global loss. If instead the goal is to conserve forest interior in the areas experiencing relatively rapid rates of loss, attention might instead be focused on the Temperate Coniferous Forests, the Mediterranean Forests, Woodlands & Scrub, and the Tropical & Subtropical Dry Broadleaf Forests biomes, which together contained only 8% of the global total in 2000 but had the highest rates of loss. Finally, if the goal is to identify where the patterns of forest change removed the most forest interior per unit of forest area lost, then attention would be drawn to biomes with the highest elasticity including the Tropical & Subtropical Coniferous Forests, the Temperate Broadleaf & Mixed Forests, and the Temperate Grasslands, Savannas & Shrublands biomes.

Global attention is often focused on the dynamics of tropical forests, but our analysis indicated that extra-tropical forest interior area comprised approximately half of the global total in forest biomes. Furthermore, forest interior loss rates in temperate forests approximated the rates in tropical forests. The two temperate forest biomes had higher rates of interior loss and larger elasticity values than two of the three tropical forest biomes. Nevertheless, losses in tropical forests are very important globally; the loss of forest interior area from the Tropical & Subtropical Moist Broadleaf Forests biome alone was more than double the area loss from the two temperate forest biomes.

There are differences between our measurements of global total forest area changes (Table 2) and those reported by Hansen et al (2013). Our measurement of gross loss (2.06 million km^2) is smaller than the value of 2.29 million km^2 reported by Hansen et al (2013), and our measurement of gross gain (0.35 million km^2) is much lower than the 0.80 million km^2 reported by Hansen et al (2013). The differences are due to different definitions of forest gain and forest loss. In our study, forest gains and losses were contingent on tree over in 2000 (Table 1). Forest loss occurred only if tree cover was greater than zero in 2000, forest gain occurred only if tree cover was zero in 2000, and instances of both tree cover loss and gain were considered to represent no change. In contrast, gross forest gains and losses were apparently not contingent on tree cover in 2000 in the statistics reported by Hansen et al (2013). We found that the tree cover loss map includes 0.06 million km^2 loss where tree cover in 2000 was zero, and 0.18 million km^2 where both loss and gain occurred. The tree cover gain map includes 0.28 million km^2 gain where tree cover was greater than zero in 2000 and 0.18 million km^2 where both loss and gain occurred. Taken together, those results explain almost all of the differences between our estimates of forest area changes and those reported by Hansen et al (2013).

Our global results for 2000 are consistent with fragmentation statistics reported by Haddad et al (2015) who measured distance from forest edge on a different 0.09 ha resolution global forest map derived from Landsat data (Sexton et al 2013). Haddad et al (2015) reported (in their Figure 1B) that approximately 60% of total forest area was within 700 m of edge. We derived a comparable estimate by noting that the distance from the center to a corner of our 33 pixels x 33 pixels window is 700 m. Thus, the maximum distance to edge for the extant forest pixels for which FAD < 1.0 is 700 m (Riitters and Wickham 2003). By that procedure we estimated that 62% of total forest area was no more than 700 m from nearest edge in 2000. The remarkable similarity of the two results was unexpected because of differences in the forest maps, but our result nevertheless supports the view that the majority of the global forest area in 2000 was subjected to the degrading effects of fragmentation (Haddad et al 2015). Furthermore, our analysis indicates that the percentage of extant forest that is subjected to edge effects within 700 m increased from 62% in 2000 to 77% in 2012.

Forest pattern and change are relevant ecologically as descriptors of extrinsic environmental drivers of ecological processes (O'Neill et al 1997; Rose et al 2014; Haddad et al 2015). But every change happens at a particular place, and that unique set of circumstances ultimately determines the ecological consequences. Several of the complicating factors are as follows. Anthropogenic land use in the vicinity is a critical factor influencing ecological impacts (Ricketts 2001). Temporary deforestation (e.g., fire) is less important than permanent deforestation (e.g., urban development). Silvicultural operations (tree farms) usually create forest environments that differ from those arising through natural succession. A given change may be detrimental to one ecological service and beneficial to another. Tree cover data may be insensitive to "cryptic deforestation" (Turner et al 2007) due to partial harvest or degradation (e.g., shade crops). Finally, tree cover data alone do not indicate forest type, quality, or age. Land cover maps derived from tree cover are alone not sufficient to address any of those complicating factors.

As a practical matter, interpreting the results of a global analysis will usually require a trade-off of local precision for global consistency (Pelletier and Goetz 2015). Advances in remote sensing technology are likely to improve the frequency, quality, and content of global forest maps, but there will always be a need for finer-scale ancillary data to answer increasingly detailed questions about the causes or consequences of forest fragmentation. Since the detailed questions usually refer to specific locations, one general approach is to integrate detailed local information if it is available (Riitters et al 2012). For example, mensuration information can come from *in situ* inventories, causal data may be derived from land use maps or models, and biodiversity field data can be examined to evaluate the consequences of forest fragmentation. The current limitations and complications of our analysis do not obviate the need for, and value of globally consistent forest assessments (Mather 2005). Until better techniques are developed, a strategy for global monitoring using remote sensing data is to minimize the failure to detect real change, even at the expense of a higher rate detecting unimportant changes. Under this strategy, it is worthwhile to know where the changes in an important environmental driver are occurring.

Despite its inherent limitations, mapping tree cover through remote sensing is presently the only feasible way to consistently map and monitor the global status and trends of forest interior area. In most regions, there are no baselines for quantitative comparisons with “natural” amounts of forest interior, but the elasticity of loss relative to total forest area at least shows where disturbances have the largest fragmenting effects on the remaining forest. As forest area is lost and the remainder becomes more fragmented, there may be scale- and process-dependent “tipping points” (Luck 2005) at which the residual forest no longer functions as forest interior (Gascon et al 2000). Monitoring sudden changes in forest interior area may provide an early warning of impending tipping points in dependent ecological functions (Andersen et al 2009; Scheffer et al 2009; Suding and Hobbs 2009). Earth observation provides a unique perspective for identifying some of the most important environmental problems resulting from cumulative and interacting changes over large regions and time intervals (O’Neill et al 1997; Carpenter et al 2006).

Acknowledgments

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Table 1. Logic used to derive forest maps in 2000 and 2012 from the Global Forest Change Database.

Variables in the Global Forest Change Database[a]			Derived forest cover maps		Derived forest change
Tree cover percent in 2000	Forest gain	Forest loss	2000	2012	2000 to 2012
0	no	no	non-forest	non-forest	no change
0	yes	no	non-forest	forest	gross gain
0	no	yes	non-forest	non-forest	no change
0	yes	yes	non-forest	non-forest	no change
> 0	no	no	forest	forest	no change
> 0	yes	no	forest	forest	no change
> 0	no	yes	forest	non-forest	gross loss
> 0	yes	yes	forest	forest	no change

[a]Hansen et al (2013)

Table 2. Summary of global changes in forest and forest interior area from 2000 to 2012.

	2000	Gross loss	Gross Gain	Net change	2012	Net change
	10^6 km^2					%
All forest area	53.41	2.06	0.35	-1.71	51.70	-3.2
Forest interior area	37.79	4.24	0.48	-3.76	34.04	-9.9
Direct component of forest interior change	--	1.44	0.12	-1.32	--	--
Indirect component of forest interior change	--	2.79	0.36	-2.44	--	--

Table 3. Biome-level summary of global forest area and change from 2000 to 2012. A version of this table showing statistics by biome and continent is in Supplementary information.

	All forest area			Forest interior area			Change metrics	
	2000	Change		2000	Change		Elas-ticity	Direct change
Forest biomes	10^3 km^2	10^3 km^2	%	10^3 km^2	10^3 km^2	%	--	%
Tropical & Subtropical Moist Broadleaf Forests	15957	-582	-3.6	13375	-1437	-10.7	2.9	32
Tropical & Subtropical Dry Broadleaf Forests	1693	-114	-6.7	1042	-173	-16.6	2.5	42
Tropical & Subtropical Coniferous Forests	430	-6	-1.5	188	-18	-9.7	6.7	19
Temperate Broadleaf & Mixed Forests	5895	-126	-2.1	3085	-394	-12.8	5.9	25
Temperate Coniferous Forests	2544	-121	-4.7	1549	-264	-17.1	3.6	34
Boreal Forests & Taiga	11012	-419	-3.8	7558	-785	-10.4	2.7	46
All forest biomes	37530	-1368	-3.6	26796	-3071	-11.5	3.1	35
Non-forest biomes								
Tropical & Subtropical Grasslands, Savannas & Shrublands	10896	-206	-1.9	8913	-495	-5.6	2.9	32
Temperate Grasslands, Savannas & Shrublands	952	-21	-2.2	229	-28	-12.0	5.5	31
Flooded Grasslands & Savannas	539	-7	-1.3	399	-15	-3.8	2.9	29
Montane Grasslands & Shrublands	809	-9	-1.1	521	-25	-4.7	4.3	31
Tundra	1108	-30	-2.7	351	-34	-9.8	3.6	55
Mediterranean Forests, Woodlands & Scrub	749	-42	-5.6	260	-49	-19.0	3.4	52
Deserts & Xeric Shrublands	628	-22	-3.5	176	-23	-13.0	3.7	23
Mangroves	201	-6	-3.2	147	-16	-11.0	3.4	31
All non-forest biomes	15881	-343	-2.2	10995	-685	-6.2	2.9	34
Global	53411	-1711	-3.2	37791	-3756	-9.9	3.1	35

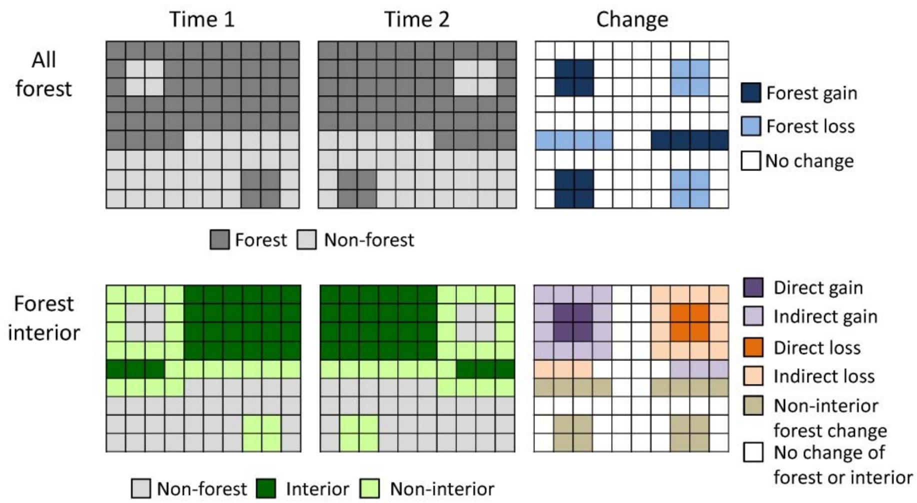
Figure Captions

Figure 1. Illustration of direct and indirect changes of forest interior area in relation to changes of forest area. In this conceptual model, "forest interior" is the subset of total forest area that is more than one unit distance away from forest edge (compare first two figures in top and bottom rows). Forest gains and losses (top row, right) result in either no impact on forest interior, direct gain or loss of forest interior, or indirect gain or loss of forest interior (bottom row, right). This conceptual model was implemented with a different definition of forest interior as described in the text.

Figure 2. Forest area and change in relation to forest area density. Forest area in 2000 (triangles) and gross forest losses (open circles) are shown in relation to forest area density in 2000. Gross forest gains (closed circles) are shown in relation to forest area density in 2012. Forest interior area includes the symbols to the right of the vertical reference line.

Figure 3. Net changes in forest area (top) and forest interior area (middle) by ecological region from 2000 through 2012. Terrestrial ecological regions are shaded according to net changes, using the same legend to facilitate comparisons. The inset maps (bottom) identify forest biomes (left) and ecological regions with >50% forest area (right).

Figure 1.



Time 1
Time 2
Change
All forest
Forest gain
Forest loss
No change
Forest
Non-forest
Forest interior
Direct gain
Indirect gain
Direct loss
Indirect loss
Non-interior forest change
No change of forest or interior
Non-forest
Interior
Non-interior

390

Figure 2

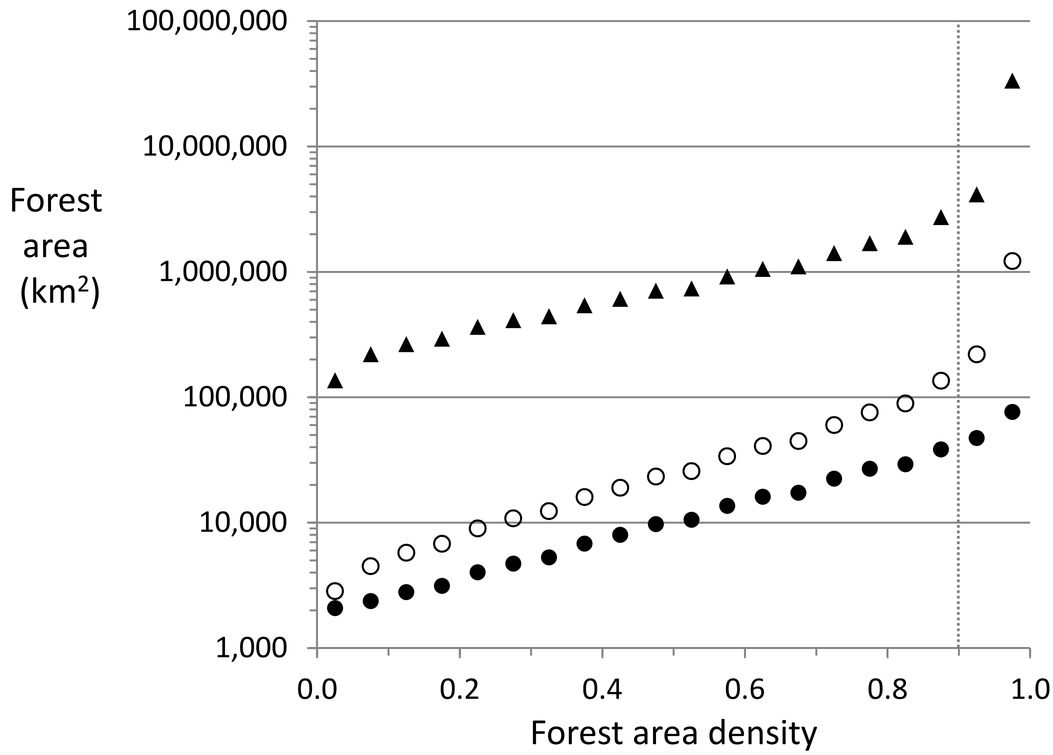
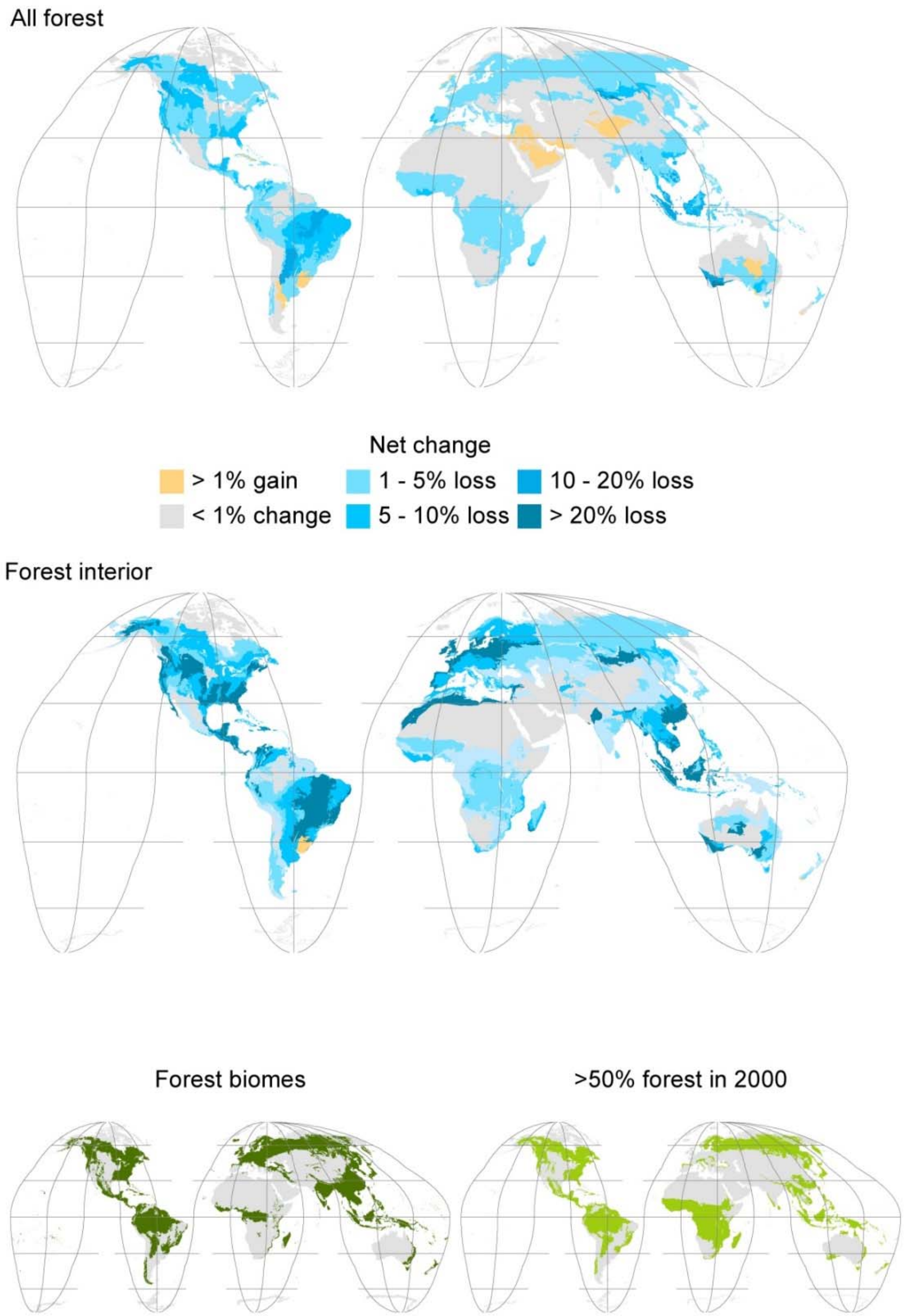

100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
Forest area (km²)
0.0
0.2
0.4
0.6
0.8
1.0
Forest area density

Figure 3


All forest
Net change
> 1% gain
< 1% change
1 - 5% loss
5 - 10% loss
10 - 20% loss
> 20% loss
Forest interior
Forest biomes
>50% forest in 2000

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Supplementary information

A note on measurement scale

All aspects of forest spatial pattern are scale-contingent and there is no single scale that is best for all applications. The first scale parameter in our analysis was window size. We used a 0.9801 km^2 window (33 pixels X 33 pixels) and refer to that as a 1 km^2 neighborhood. For land cover maps similar to those derived from the global forest change database, smaller neighborhoods tend to identify more forest interior area because it is usually easier to achieve a specified threshold FAD in a smaller neighborhood than in a larger neighborhood (Riitters et al., 2002). For the smallest possible neighborhood size (1 pixel X 1 pixel), FAD = 1 for all forest, and thus all forest area is by definition forest interior area. To the extent that larger neighborhood sizes identify less forest interior area, the scales of forest fragmentation can be determined by analyzing FAD in progressively larger neighborhood sizes. Results obtained for other reasonable choices of neighborhood size would not change our essential conclusion that elasticity of forest interior area with respect to total forest area was larger than one, even though the absolute values of the forest interior area estimates would naturally be different. The second scale parameter in our analysis was the threshold FAD value chosen to define forest interior. Lower thresholds identify more forest interior area because it is easier to achieve a lower threshold than a higher threshold. For the smallest possible (and trivial) threshold (FAD > 0), all forest area is forest interior area.

A note on the definition of forest

This study adopted the same definition of forest in 2000 as was used by Hansen et al. (2013). Forest was defined as a pixel with non-zero tree cover percentage, where a tree is vegetation taller than 5 m (Hansen et al., 2013). The effect of that definition on comparisons with area estimates in earlier global assessments (e.g., FAO 2010) has been discussed (Mather 2005; Hansen et al. 2013; Coulston et al., 2014). That definition was the only parsimonious method to derive a comparable forest map for the year 2012 employing the maps of forest gain and forest loss from the global forest change database, which are said to describe transitions to and from a state of non-zero tree cover (Hansen et al. 2013).

Our definition of forest can include areas not used (or managed) as forest, for example tree cover in agricultural and urban landscapes. We believe that such landscapes contain a small share of the total forest area and an even smaller share of the forest interior area because most forest and almost all forest interior occurs in forest-dominated landscapes (Riitters et al. 2000, 2002). We focused on the change in forest interior area relative to change in total forest area, and it is not likely that the large changes in forest interior area that we observed were due to forest change in agricultural or urban landscapes.

Supplemental table

Table 3 in the main text summarized global statistics within each terrestrial biome. A given biome may appear on different continents, thereby preventing comparisons across continents. For that reason, Table S.1 was prepared to provide the same summary of global statistics by biome and realm (Olsen et al., 2001).

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Table S.1. Forest area and net change, forest interior area and net change, and components of net change of forest interior area from 2000 to 2012 summarized by terrestrial biome and realm (Olsen et al., 2001). These statistics are comparable to those shown in Table 3 in the main text.

		All forest area			Forest interior area				Components of interior area change		
		2000	Change		2000	Change		Elasticity	Net direct	Net indirect	Direct
Biome	Realm	10^3 km^2	10^3 km^2	%	10^3 km^2	10^3 km^2	%	--	10^3 km^2	10^3 km^2	%
Tropical & Subtropical Moist Broadleaf Forests	Afrotropics	3330.4	-75.8	-2.3	3222.2	-249.9	-7.8	3.4	-75.5	-174.4	69.8
	Australasia	1072.7	-17.2	-1.6	991.9	-52.9	-5.3	3.3	-15.4	-37.5	70.8
	IndoMalay	3476.0	-185.6	-5.3	2423.7	-506.7	-20.9	3.9	-155.5	-351.2	69.3
	Neotropics	7797.2	-300.0	-3.8	6654.5	-620.7	-9.3	2.4	-213.7	-407.0	65.6
	Palearctic	280.3	-3.4	-1.2	82.8	-6.9	-8.4	7.0	-1.2	-5.7	81.9
	Biome subtotal	15956.6	-582.1	-3.6	13375.1	-1437.2	-10.7	2.9	-461.5	-975.7	32.1
Tropical & Subtropical Dry Broadleaf Forests	Afrotropics	167.0	-3.1	-1.9	126.5	-10.6	-8.4	4.5	-2.9	-7.7	72.9
	Australasia	54.7	-0.9	-1.7	24.0	-2.2	-9.3	5.6	-0.4	-1.8	80.9
	IndoMalay	311.3	-16.7	-5.4	140.5	-25.3	-18.0	3.4	-9.4	-16.0	63.0
	Nearctic	8.8	-0.1	-0.6	1.8	0.0	-2.1	3.6	0.0	0.0	90.9
	Neotropics	1150.8	-92.9	-8.1	749.1	-134.6	-18.0	2.2	-60.6	-74.0	45.0
	Biome subtotal	1692.6	-113.7	-6.7	1041.9	-172.7	-16.6	2.5	-73.3	-99.5	42.4
Tropical & Subtropical Coniferous Forests	IndoMalay	55.7	-0.4	-0.7	18.5	-1.1	-6.0	8.5	-0.2	-0.9	82.3
	Nearctic	150.4	-0.6	-0.4	52.3	-1.4	-2.6	6.8	-0.2	-1.1	83.0
	Neotropics	223.9	-5.3	-2.4	116.7	-15.8	-13.5	5.7	-3.0	-12.8	80.7
	Biome subtotal	430.1	-6.3	-1.5	187.5	-18.3	-9.7	6.7	-3.5	-14.8	19.0
Temperate Broadleaf & Mixed Forests	Australasia	353.6	-4.5	-1.3	235.9	-13.7	-5.8	4.6	-4.7	-9.0	66.0
	IndoMalay	103.1	-0.8	-0.7	65.3	-2.3	-3.6	4.9	-0.5	-1.9	79.3
	Nearctic	1902.7	-68.8	-3.6	1117.1	-203.2	-18.2	5.0	-50.7	-152.5	75.0
	Neotropics	208.6	-2.2	-1.1	106.1	-5.7	-5.4	5.1	-2.0	-3.7	64.9
	Palearctic	3326.7	-50.3	-1.5	1560.3	-168.9	-10.8	7.2	-39.4	-129.5	76.7
	Biome subtotal	5894.8	-126.5	-2.1	3084.7	-393.8	-12.8	5.9	-97.3	-296.6	24.7
Temperate Coniferous Forests	IndoMalay	31.6	-0.1	-0.4	13.2	-0.2	-1.3	3.6	0.0	-0.1	88.6
	Nearctic	1632.2	-97.2	-6.0	1013.2	-208.7	-20.6	3.5	-72.6	-136.0	65.2
	Palearctic	879.9	-23.2	-2.6	522.9	-55.4	-10.6	4.0	-17.0	-38.4	69.3
	Biome subtotal	2543.7	-120.6	-4.7	1549.3	-264.2	-17.1	3.6	-89.6	-174.6	33.9
Boreal Forests & Taiga	Nearctic	3692.8	-174.8	-4.7	2716.3	-291.4	-10.7	2.3	-160.3	-131.1	45.0
	Palearctic	7319.4	-243.7	-3.3	4841.3	-493.2	-10.2	3.1	-197.0	-296.2	60.1
	Biome subtotal	11012.2	-418.6	-3.8	7557.7	-784.6	-10.4	2.7	-357.3	-427.3	45.5

		All forest area			Forest interior area				Components of interior area change		
		2000	Change		2000	Change		Elasticity	Net direct	Net indirect	Direct
Tropical & Subtropical Grasslands, Savannas & Shrublands	Afrotropics	9021.3	-132.8	-1.5	8138.9	-407.8	-5.0	3.4	-129.6	-278.2	68.2
	Australasia	575.6	-2.0	-0.3	323.9	-3.7	-1.1	3.3	-0.9	-2.8	76.5
	IndoMalay	10.3	-0.1	-1.4	5.7	-0.2	-3.0	2.2	0.0	-0.1	81.4
	Nearctic	21.3	-0.6	-2.8	4.1	-0.7	-16.3	5.8	-0.1	-0.5	79.9
	Neotropics	1267.6	-70.3	-5.5	440.2	-82.8	-18.8	3.4	-30.0	-52.9	36.2
	Biome subtotal	10896.1	-205.8	-1.9	8912.8	-495.1	-5.6	2.9	-160.6	-334.6	32.4
Temperate Grasslands, Savannas & Shrublands	Afrotropics	0.0	0.0	0.0	0.0	0.0	--	--	--	--	--
	Australasia	82.7	-2.3	-2.8	24.8	-2.4	-9.7	3.4	-1.0	-1.4	56.9
	Nearctic	375.5	-8.5	-2.3	77.4	-9.2	-11.9	5.2	-2.4	-6.8	73.8
	Neotropics	38.3	-1.1	-2.8	3.9	-0.4	-10.1	3.7	-0.1	-0.3	68.9
	Palearctic	455.8	-8.9	-2.0	123.2	-15.6	-12.6	6.4	-5.0	-10.6	67.8
	Biome subtotal	952.3	-20.8	-2.2	229.3	-27.5	-12.0	5.5	-8.6	-19.0	31.1
Flooded Grasslands & Savannas	Afrotropics	345.2	-3.1	-0.9	312.4	-9.5	-3.0	3.4	-3.0	-6.5	68.5
	IndoMalay	0.0	0.0	-0.2	0.0	0.0	--	--	--	--	--
	Neotropics	133.3	-3.6	-2.7	62.2	-4.7	-7.6	2.8	-1.2	-3.5	74.3
	Palearctic	60.0	-0.4	-0.6	24.0	-1.0	-4.2	6.9	-0.2	-0.8	78.6
	Biome subtotal	538.5	-7.1	-1.3	398.6	-15.2	-3.8	2.9	-4.4	-10.8	29.0
Montane Grasslands & Shrublands	Afrotropics	623.9	-6.7	-1.1	448.4	-20.7	-4.6	4.3	-6.3	-14.3	69.3
	Australasia	37.5	-0.8	-2.1	26.9	-1.8	-6.7	3.3	-0.6	-1.2	64.3
	IndoMalay	4.2	-0.1	-3.0	3.9	-0.5	-13.8	4.6	-0.1	-0.4	77.3
	Neotropics	26.4	-0.1	-0.5	9.2	-0.3	-3.2	6.4	-0.1	-0.2	80.9
	Palearctic	117.2	-1.2	-1.0	33.1	-1.3	-4.1	3.9	-0.4	-0.9	67.1
	Biome subtotal	809.1	-8.9	-1.1	521.4	-24.7	-4.7	4.3	-7.6	-17.1	30.8
Tundra	Nearctic	402.5	-17.4	-4.3	173.9	-24.4	-14.0	3.2	-14.3	-10.0	41.2
	Palearctic	705.5	-12.9	-1.8	177.0	-10.0	-5.7	3.1	-4.4	-5.6	55.9
	Biome subtotal	1108.0	-30.3	-2.7	350.9	-34.4	-9.8	3.6	-18.8	-15.6	54.5
Mediterranean Forests, Woodlands & Scrub	Afrotropics	42.5	-0.8	-1.8	21.6	-2.7	-12.4	6.7	-0.6	-2.1	77.2
	Australasia	239.5	-28.5	-11.9	130.1	-31.8	-24.4	2.1	-21.2	-10.6	33.3
	Nearctic	47.5	-4.2	-8.8	15.4	-3.1	-19.8	2.3	-1.5	-1.5	50.7
	Neotropics	20.7	0.2	1.0	3.8	-0.4	-9.4	-9.5	-0.1	-0.3	77.0
	Palearctic	398.5	-8.4	-2.1	88.9	-11.5	-12.9	6.1	-2.3	-9.1	79.8
	Biome subtotal	748.6	-41.6	-5.6	259.9	-49.3	-19.0	3.4	-25.7	-23.6	52.1
Deserts & Xeric Shrublands	Afrotropics	136.6	-3.0	-2.2	60.5	-9.7	-16.0	7.2	-2.7	-7.0	72.4
	Australasia	17.0	-0.1	-0.8	1.6	0.0	-0.4	0.5	0.0	0.0	88.6
	IndoMalay	14.2	0.0	-0.3	1.4	0.0	-1.1	3.6	0.0	0.0	86.8
	Nearctic	120.5	-2.9	-2.4	16.9	-1.2	-7.0	2.9	-0.4	-0.8	70.2

		All forest area			Forest interior area				Components of interior area change		
		2000	Change		2000	Change		Elasticity	Net direct	Net indirect	Direct
	Neotropics	309.5	-15.2	-4.9	92.7	-11.7	-12.6	2.6	-2.1	-9.6	82.1
	Palearctic	29.8	-0.9	-2.9	2.7	-0.3	-10.4	3.6	-0.1	-0.1	52.7
	Biome subtotal	627.6	-22.2	-3.5	175.8	-22.9	-13.0	3.7	-5.3	-17.6	23.0
Mangroves	Afrotropics	65.8	-1.1	-1.7	59.8	-3.5	-5.9	3.4	-1.1	-2.4	69.1
	Australasia	22.8	-0.1	-0.4	22.0	-0.3	-1.3	2.9	-0.1	-0.2	70.1
	IndoMalay	49.5	-3.9	-7.9	29.3	-8.8	-30.0	3.8	-3.1	-5.7	64.9
	Neotropics	63.0	-1.3	-2.1	35.5	-3.6	-10.1	4.8	-0.8	-2.8	78.3
	Biome subtotal	201.1	-6.5	-3.2	146.6	-16.1	-11.0	3.4	-5.0	-11.1	31.1
	Global total	53411.2	-1711.0	-3.2	37791.4	-3756.2	-9.9	3.1	-1318.3	-2437.9	35.1