Landscape Ecol (2016) 31:137–148
DOI 10.1007/s10980-015-0270-9

RESEARCH ARTICLE

A global evaluation of forest interior area dynamics using tree cover data from 2000 to 2012

Kurt Riitters · James Wickham · Jennifer K. Costanza · Peter Vogt

Received: 3 April 2015 / Accepted: 25 August 2015 / Published online: 7 September 2015

Abstract

Context Published maps of global tree cover derived from Landsat data have indicated substantial changes in forest area from 2000 to 2012. 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 sustainability.

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

Electronic supplementary material The online version of this article (doi:10.1007/s10980-015-0270-9) contains supplementary material, which is available to authorized users.

Special issue: Macrosystems ecology: Novel methods and new understanding of multi-scale patterns and processes.

Guest Editors: S. Fei, Q. Guo, and K. Potter.

K. Riitters (✉)
Southern Research Station, United States Department of Agriculture, Forest Service, 3041 Cornwallis Road,
Research Triangle Park, NC 27709, USA
e-mail: kriitters@fs.fed.us

J. Wickham
National Exposure Research Laboratory, United States Environmental Protection Agency,
Research Triangle Park, NC 27711, USA

J. K. Costanza
North Carolina Cooperative Fish and Wildlife Research Unit, Department of Applied Ecology, North Carolina State University, Raleigh, NC 27695, USA

Present Address:
J. K. Costanza
Department of Forestry and Environmental Resources,
North Carolina State University, Raleigh, NC 27695, USA

P. Vogt
Joint Research Centre (JRC), European Commission,
21027 Ispra, Italy

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

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 × 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 is an incomplete indicator because forest gains may offset losses (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). While single-date global analyses of forest fragmentation have been conducted at 1 km^2 resolution (Riitters et al. 2000) and 0.09 ha resolution (Haddad et al. 2015), the new forest maps for 2000 and 2012 permit an analysis of change in global forest fragmentation, as defined by change in forest interior.

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 may extend hundreds of meters from forest edge (Murcia 1995; Laurance 2000; Ries et al. 2004), making it unlikely that an isolated 30 × 30 m forest parcel will support 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 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 equivalent to a commonly used 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 area changes over time, the patterns of gains and losses cause direct and indirect changes of

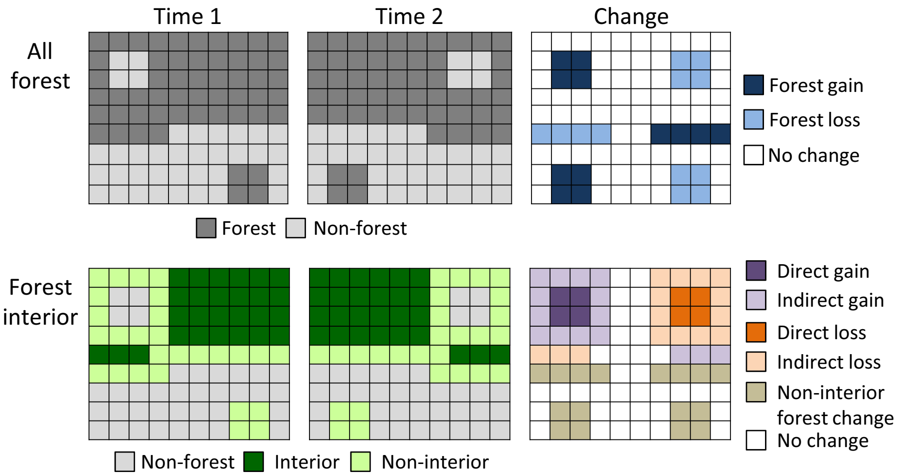

Fig. 1 Illustration of direct and indirect changes of forest interior area in relation to changes of forest area. In this conceptual model, "forest interior" is defined as the subset of total forest area that is more than one unit distance away from forest edge (compare first two figures in *top* and *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*)

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. To illustrate the concepts, consider a definition of forest interior as a forest pixel that is not forest edge (Fig. 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. Mapping forest interior at the same resolution as the forest map makes it possible to identify the direct and indirect components of forest interior change by combining the two maps of change. While this framework illustrates the concepts of direct and indirect changes, we defined forest interior by the proportion of forest in the neighborhood of a forest pixel rather than the distance of that pixel to forest edge. Our objectives were to map the forest interior area globally, to quantify its rate of loss in different regions, and to estimate the direct and indirect components of change.

Methods

Forest cover in 2000 and 2012

We used the Global Forest Change Database (GFCD, version 1: Hansen et al. 2013), obtained from Google Earth Engine (http://earthenginepartners.appspot.com/science-2013-global-forest) as a set of 10° × 10° map tiles in a geographic projection; each tile was 36,000 × 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.

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	2000–2012
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)

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 comparable 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).

Forest interior analysis

We mapped forest interior area by using a moving window analysis (Riitters et al. 1997) of the forest maps for 2000 and 2012. This approach has been 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).

Our approach to measuring forest interior change follows the concepts illustrated in Fig. 1, except that we used a moving window approach to identify forest interior. At each date, each pixel was described by its forest area density (FAD), defined as the proportion of a surrounding 33 × 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 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.

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. There was a direct loss (or gain) of forest interior if the FAD of a pixel that was lost (or gained) was ≥ 0.9. The indirect component of forest interior change was estimated by evaluating net change in FAD for pixels that were forest at both dates. The forest interior status of a persistent 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 and forest interior area by elasticity, defined as the net percent change in forest interior area divided by the net percent change in total forest area within a given geographic region. Regions were defined by maps (World Wildlife Fund 2004) of the 14 terrestrial biomes and 768 terrestrial ecological regions described by Olson et al. (2001). We called six of the 14 biomes "forest biomes" based on an expectation that the original land cover in those biomes was dominated by forest. The remaining "non-forest biomes" were included because we were interested in all global forest area, and the non-forest biomes 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. In this study 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 national and global forest maps with various spatial resolutions. 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 of loss rates and elasticity but not 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

In 2000 there was 53.41 million km^2 of forest, of which 37.79 million km^2 (71 %) was forest interior area (Table 2). 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.

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 (Fig. 2). For FAD

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

	2000 10^6 km^2	Gross loss 10^6 km^2	Gross gain 10^6 km^2	Net change 10^6 km^2	2012 10^6 km^2	Net change %
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	–	–

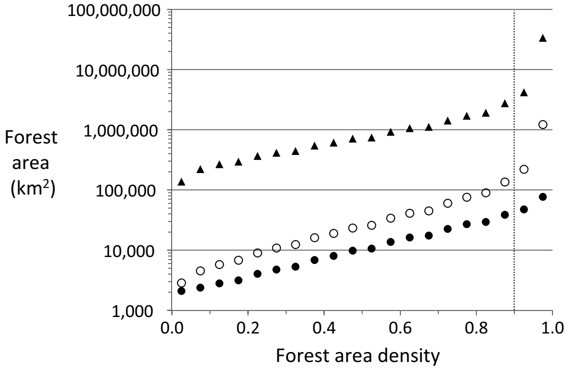

Fig. 2 Forest area and change in relation to forest area density. Forest area in 2000 (*triangles*) and gross forest losses (*open circles*) are shown in relation to forest area density in 2000. Gross forest gains (*closed circles*) are shown in relation to forest area density in 2012. Forest interior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

≥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).

Forest biomes

Tree cover dynamics in the six forest biomes accounted for 80 and 82 %, respectively, of the global net losses of all forest area and forest interior area (Table 3). On a per-biome basis the loss of forest interior area was between 10 and 17 % of the area in 2000, with the largest percentage loss in the Temperate Coniferous Forests biome. The largest forest interior 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).

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 and Subtropical Grasslands, Savannas and 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 and Shrublands (12 %), Deserts and Xeric Shrublands (13 %), and Mediterranean Forests, Woodlands and 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 three regions (in western Canada, southern China, and southern New Zealand) 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 three regions (one in eastern Canada and two at the borders of Uruguay, Argentina, and Brazil) 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 relatively small forest cover percentages in 2000. Several ecological regions exhibited net gains of forest area but not forest interior area.

Table 3 Biome-level summary of global forest area and change from 2000 to 2012

	All forest area			Forest interior area			Change metrics	
	2000	Change		2000	Change		Elasticity	Direct change
	10^3 km^2	10^3 km^2	%	10^3 km^2	10^3 km^2	%	–	%
Forest biomes								
Tropical and subtropical moist broadleaf forests	15,957	−582	−3.6	13375	−1437	−10.7	2.9	32
Tropical and subtropical dry broadleaf forests	1693	−114	−6.7	1042	−173	−16.6	2.5	42
Tropical and subtropical coniferous forests	430	−6	−1.5	188	−18	−9.7	6.7	19
Temperate broadleaf and 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 and taiga	11,012	−419	−3.8	7558	−785	−10.4	2.7	46
All forest biomes	37,530	−1368	−3.6	26796	−3071	−11.5	3.1	35
Non-forest biomes								
Tropical and subtropical grasslands, savannas and shrublands	10,896	−206	−1.9	8913	−495	−5.6	2.9	32
Temperate grasslands, savannas and shrublands	952	−21	−2.2	229	−28	−12.0	5.5	31
Flooded grasslands and savannas	539	−7	−1.3	399	−15	−3.8	2.9	29
Montane grasslands and 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 and scrub	749	−42	−5.6	260	−49	−19.0	3.4	52
Deserts and 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	15,881	−343	−2.2	10,995	−685	−6.2	2.9	34
Global	53,411	−1711	−3.2	37,791	−3756	−9.9	3.1	35

Note: A version of this table showing statistics by biome and continent is in Supplementary information

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 (Fig. 3). Furthermore, the substantial regional variation in elasticity indicates that a given amount of forest loss can result in substantially different impacts on fragmentation in different regions. 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

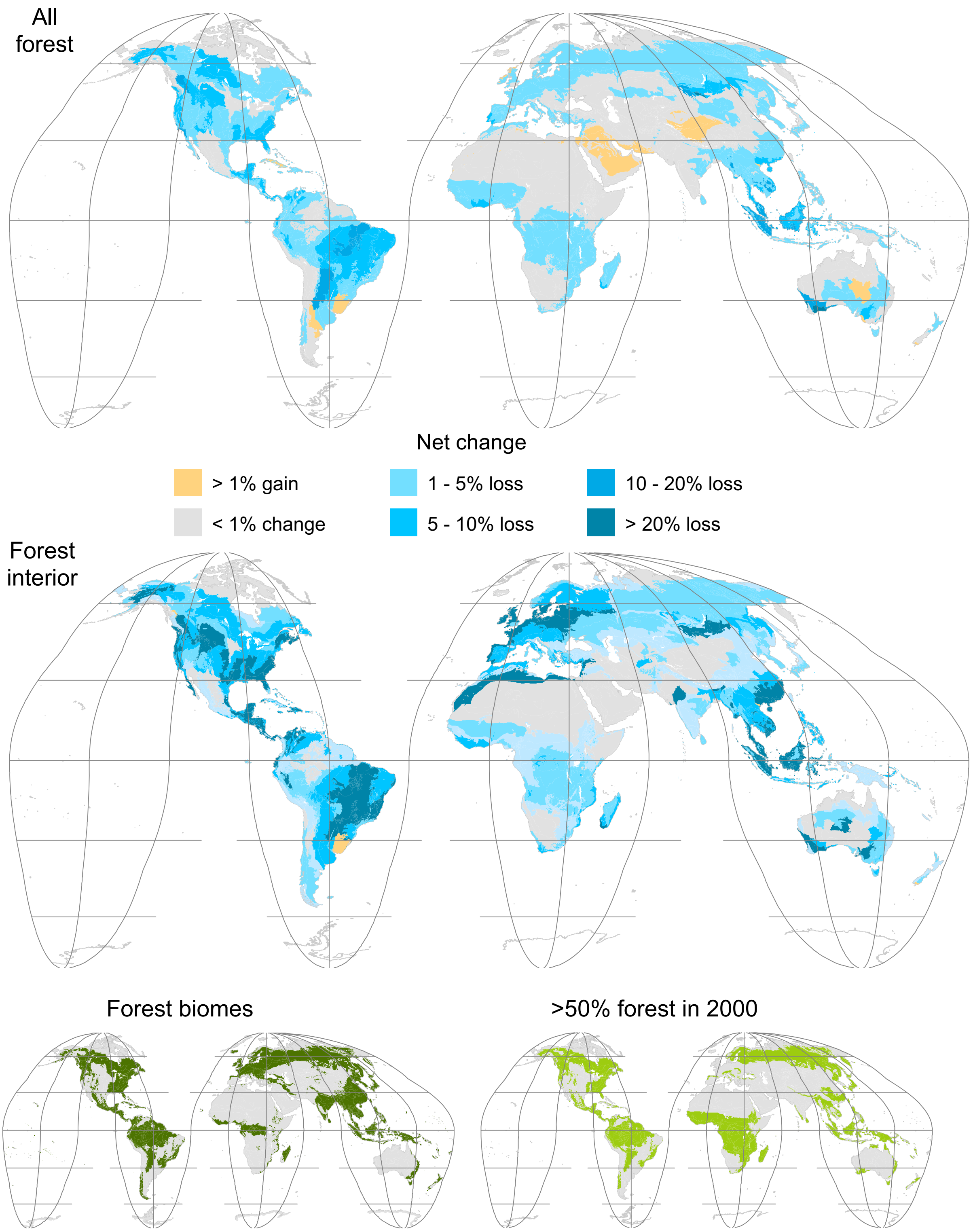

Fig. 3 Net changes in forest area (*top*) and forest interior area (*middle*) by ecological region from 2000 through 2012. Terrestrial ecological regions are shaded according to net changes, using the same legend to facilitate comparisons. The inset maps (*bottom*) identify forest biomes (*left*) and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

2000 and accounted for 38 % of global loss. The Tropical & Subtropical Grasslands, Savannas and 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 and Scrub, and the Tropical and 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 and Subtropical Coniferous Forests, the Temperate Broadleaf and Mixed Forests, and the Temperate Grasslands, Savannas and 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 cover 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 circa 2000 (Sexton et al. 2013). Haddad et al. (2015) reported (in their Fig. 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 × 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 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 was subjected to edge effects within 700 m increased from 62 % in 2000 to 77 % in 2012.

Forest pattern changes 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 (an example in Fig. 3 is the net gain of forest and forest interior area in savanna regions in South America). 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 not sufficient to address any of those complicating factors without additional information.

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 and 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 or remotely sensed biophysical data can be examined to evaluate some of the consequences of forest fragmentation. Detailed investigations are currently opportunistic and global consistency remains a worthwhile yet elusive goal. But the current limitations and complications of analyses such as ours 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 may be to minimize the failure to detect real changes, even at the expense of detecting more but sometimes unimportant changes. Under this strategy, knowing where the changes in an important environmental driver are occurring can guide where detailed investigations may be needed.

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 We thank M. Hansen, his colleagues, and Google Earth Engine for the global forest change maps. The United States Environmental Protection Agency (EPA), through its Office of Research and Development, partially funded and collaborated in the research described here. It has been subjected to EPA review and approved for publication.

References

Andersen T, Carstensen J, Hernández-Garcia E, Duarte CM (2009) Ecological thresholds and regime shifts: approaches to identification. Trends Ecol Evol 24:49–57

Andrén H (1994) Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. Oikos 71:355–366

Asner GP (2014) Satellites and psychology for improved forest monitoring. Proc Natl Acad Sci 111:567–568

Cadenasso ML, Pickett STA (2001) Effect of edge structure on the flux of species into forest interiors. Conserv Biol 15:91–97

Carpenter SR, DeFries R, Dietz T, Mooney HA, Polasky S, Reid WV, Scholes RJ (2006) Millennium ecosystem assessment: research needs. Science 314:257–258

Chazdon RL (2008) Beyond deforestation: restoring forests and ecosystem services on degraded lands. Science 320:1458–1460

Fahrig L (2003) Effects of habitat fragmentation on biodiversity. Annu Rev Ecol Evol Syst 34:487–515

FAO (Food and Agriculture Organization of the United Nations) (2010) Global forest resource assessment 2010. FAO Forestry Paper 163, Rome

Gascon C, Williamson GB, da Fonseca GAB (2000) Receding forest edges and vanishing reserves. Science 288:1356–1358

Haddad NM, Brudvig LA, Clobert J, Davies KF, Gonzalez A, Holt RD, Lovejoy TE, Sexton JO, Austin MP, Collins CD, Cook WM, Damschen EI, Ewers RM, Foster BL, Jenkins CN, King AJ, Laurance WF, Levey DJ, Margules CR, Melbourne BA, Nicholls AO, Orrock JL, Song D-X, Townshend JR (2015) Habitat fragmentation and its lasting impact on Earth's ecosystems. Sci Adv 1:e1500052

Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, Thau D, Stehman SV, Goetz SJ, Loveland TR, Kommareddy A, Egorov A, Chini L, Justice CO, Townshend JRG (2013) High-resolution global maps of 21st-century forest cover change. Science 342:850–853. http://earthenginepartners.appspot.com/science-2013-global-forest. Accessed 5 March 2014

Harris LD (1984) The fragmented forest. University of Chicago Press, Chicago

Heinz Center (The H. John Heinz III Center for Science, Economics, and the Environment) (2008) The state of the nation's ecosystems 2008. Island Press, Washington, DC

Hosonuma N, Herold M, De Sy V, De Fries R, Brockhaus M, Verchot L, Angelsen A, Romijn E (2012) An assessment of deforestation and forest degradation drivers in developing countries. Environ Res Lett 7:044009

Innes JL, Koch B (1998) Forest biodiversity and its assessment by remote sensing. Glob Ecol Biogeogr Lett 7:397–419

Kapos V (1989) Effects of isolation on the water status of forest patches in the Brazilian Amazon. J Trop Ecol 5:173–185

Keddy PA, Drummond CG (1996) Ecological properties for the evaluation, management, and restoration of temperate deciduous forest ecosystems. Ecol Appl 6:748–762

Kurz WA (2010) An ecosystem context for global gross forest cover loss estimates. Proc Natl Acad Sci 107:9025–9026

Laurance WF (2000) Do edge effects occur over large spatial scales? Trends Ecol Ecol 15:134–135

Laurance WF (2008) Theory meets reality: how habitat fragmentation research has transcended island biogeography theory. Biol Conserv 141:1731–1744

Laurance WF, Ferreira LV, Rankin-De Merona JM, Laurance SG (1998) Rain forest fragmentation and the dynamics of Amazonian tree communities. Ecology 79:2032–2040

Loveland TR, Dwyer JL (2012) Landsat: building a strong future. Remote Sens Environ 122:22–29

Luck GW (2005) An introduction to ecological thresholds. Biol Conserv 124:299–300

Mather AS (2005) Assessing the world's forests. Glob Environ Change 15:267–280

McIntyre S, Hobbs R (1999) A framework for conceptualizing human effects on landscapes and its relevance to management and research models. Conserv Biol 13:1282–1292

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: biodiversity synthesis. World Resources Institute, Washington, DC

Murcia C (1995) Edge effects in fragmented forests: implications for conservation. Trends Ecol Evol 10:58–62

Olson DM, Dinerstein E, Wikramanayake ED, Burgess ND, Powell GVN, Underwood EC, D'Amico JA, Itoua I, Strand HE, Morrison JC, Loucks CJ, Allnutt TF, Ricketts TH, Kura Y, Lamoreux JF, Wettengel WW, Hedao P, Kassem KR (2001) Terrestrial ecoregions of the world: a new map of life on Earth. Bioscience 51:933–938

O'Neill RV, Hunsaker CT, Jones KB, Riitters KH, Wickham JD, Schwartz PM, Goodman IA, Jackson BL, Baillargeon WS (1997) Monitoring environmental quality at the landscape scale. Bioscience 47:513–519

Pelletier J, Goetz SJ (2015) Baseline data on forest loss and associated uncertainty: advances in national forest monitoring. Environ Res Lett 10:021001

Pickett STA, Cadenasso ML (1995) Landscape ecology: spatial heterogeneity in ecological systems. Science 269:331–334

Ricketts TH (2001) The matrix matters: effective isolation in fragmented landscapes. Am Nat 158:87–99

Ries L, Fletcher RJ, Battin J, Sisk TD (2004) Ecological responses to habitat edges: mechanisms, models, and variability explained. Annu Rev Ecol Evol Syst 35:491–522

Riitters KH, Wickham JD (2003) How far to the nearest road? Front Ecol Environ 1:125–129

Riitters KH, Wickham JD (2012) Decline of forest interior conditions in the conterminous United States. Sci Rep 2:653

Riitters KH, O'Neill RV, Jones KB (1997) Assessing habitat suitability at multiple scales: a landscape-level approach. Biol Conserv 81:191–202

Riitters K, Wickham J, O'Neill RV, Jones B, Smith E (2000) Global-scale patterns of forest fragmentation. Ecol Soc 4(2):3

Riitters KH, Wickham JD, O'Neill RV, Jones KB, Smith ER, Coulston JW, Wade TG, Smith JH (2002) Fragmentation of continental United States forests. Ecosystems 5:815–822

Riitters KH, Coulston JW, Wickham JD (2012) Fragmentation of forest communities in the eastern United States. For Ecol Manage 263:85–93

Robinson SK, Thompson FR III, Donovan TM, Whitehead DR, Faaborg J (1995) Regional forest fragmentation and the nesting success of migratory birds. Science 267:1987–1990

Rose RA, Byler D, Eastman JR, Fleishman E, Geller G, Goetz S, Guild L, Hamilton H, Hansen M, Headley R, Hewson J, Horning N, Kaplin BA, LaPorte N, Leidner A, Leimgruber P, Morisette J, Musinsky J, Pintea L, Prados A, Radeloff VC, Rowen M, Saatchi S, Schill S, Tabor K, Turner W, Vodacek A, Vogelmann J, Wegmann M, Wilkie D, Wilson C (2014) Ten ways remote sensing can contribute to conservation. Conserv Biol 29:350–359

Roy DP, Wulder MA, Loveland TR, Woodcock CE, Allen RG, Anderson MC, Helder D, Irons JR, Johnson DM, Kennedy R, Scambos TA, Schaaf CB, Schott JR, Sheng Y, Vermote EF, Belward AS, Bindschadler R, Cohen WB, Gao F, Hipple JD, Hostert P, Huntington J, Justice CO, Kilic A, Kovalskyy V, Lee ZP, Lymburner L, Masek JG, McCorkel J, Shuai Y, Trezza R, Vogelmann J, Wynne RH, Zhu Z (2014) Landsat-8: science and product vision for terrestrial global change research. Remote Sens Environ 145:154–172

Scheffer M, Bascompte J, Brock WA, Brovkin V, Carpenter SR, Dakos V, Held H, Van Nes EH, Rietkerk M, Sugihara G (2009) Early-warning signals for critical transitions. Nature 461:53–59

Sexton JO, Song XP, Feng M, Noojipady P, Anand A, Huang C, Kim D-H, Collins KM, Channan S, DiMiceli C, Townshend JR (2013) Global, 30-m resolution continuous fields of tree cover: landsat-based rescaling of MODIS vegetation continuous fields with lidar-based estimates of error. Int J Digit Earth 6:427–448

Suding KN, Hobbs RJ (2009) Threshold models in restoration and conservation: a developing framework. Trends Ecol Evol 24:271–279

Turner BL II, Lambin EF, Reenberg A (2007) The emergence of land change science for global environmental change and sustainability. Proc Natl Acad Sci 104:2066–20671

US Environmental Protection Agency (2008) EPA's 2008 report on the environment. EPA/600/R-07/045F. National Center for Environmental Assessment, Washington, DC.

Available from the National Technical Information Service, Springfield. http://www.epa.gov/roe

USDA (United States Department of Agriculture) Forest Service (2004) National report on sustainable forests—2003. Publication FS-766. USDA Forest Service, Washington, DC

USDA (United States Department of Agriculture) Forest Service (2011) National report on sustainable forests—2010. Publication FS-979. USDA Forest Service, Washington, DC

USDA (United States Department of Agriculture) Forest Service (2012) Future of America's forest and rangelands: Forest Service 2010 Resources Planning Act assessment. General Technical Report WO-87. Washington, DC

Wade TG, Riitters KH, Wickham JD, Jones KB (2003) Distribution and causes of global forest fragmentation. Ecol Soc 7(2):7

Weathers KC, Cadenasso ML, Pickett STA (2001) Forest edges as nutrient and pollutant concentrators: potential synergisms between fragmentation, forest canopies, and the atmosphere. Conserv Biol 15:1506–1514

Wickham JD, Riitters KH, Wade TG, Coulston JW (2007) Temporal change in fragmentation at multiple scales. Landscape Ecol 22:481–489

Wickham JD, Riitters KH, Wade TG, Homer C (2008) Temporal change in fragmentation of continental US forests. Landscape Ecol 23:891–898

World Wildlife Fund (2004) Terrestrial ecoregions of the world. Version 2.0 (digital map). The World Wildlife Fund, Washington, DC. http://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world. Accessed 4 Feb 2009

Wulder MA, Masek JG, Cohen WB, Loveland TR, Woodcock CE (2012) Opening the archive: how free data has enabled the science and monitoring promise of Landsat. Remote Sens Environ 122:2–10