Quantification of global gross forest cover loss

Matthew C. Hansen[a,1], Stephen V. Stehman[b], and Peter V. Potapov[a]

[a]Geographic Information Science Center of Excellence, South Dakota State University, Brookings, SD 57007; and [b]College of Environmental Science and Forestry, State University of New York, Syracuse, NY 13210

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A globally consistent methodology using satellite imagery was implemented to quantify gross forest cover loss (GFCL) from 2000 to 2005 and to compare GFCL among biomes, continents, and countries. GFCL is defined as the area of forest cover removed because of any disturbance, including both natural and human-induced causes. GFCL was estimated to be 1,011,000 km^2 from 2000 to 2005, representing 3.1% (0.6% per year) of the year 2000 estimated total forest area of 32,688,000 km^2. The boreal biome experienced the largest area of GFCL, followed by the humid tropical, dry tropical, and temperate biomes. GFCL expressed as the proportion of year 2000 forest cover was highest in the boreal biome and lowest in the humid tropics. Among continents, North America had the largest total area and largest proportion of year 2000 GFCL. At national scales, Brazil experienced the largest area of GFCL over the study period, 165,000 km^2, followed by Canada at 160,000 km^2. Of the countries with >1,000,000 km^2 of forest cover, the United States exhibited the greatest proportional GFCL and the Democratic Republic of Congo the least. Our results illustrate a pervasive global GFCL dynamic. However, GFCL represents only one component of net change, and the processes driving GFCL and rates of recovery from GFCL differ regionally. For example, the majority of estimated GFCL for the boreal biome is due to a naturally induced fire dynamic. To fully characterize global forest change dynamics, remote sensing efforts must extend beyond estimating GFCL to identify proximate causes of forest cover loss and to estimate recovery rates from GFCL.

change detection | global change | monitoring | remote sensing | probability sampling

The synoptic nature of satellite-based earth observation data enables the consistent characterization of forest cover across space and over time. Information on forest cover and forest cover change is necessary for carbon accounting efforts as well as for parameterizing global-scale biogeochemical, hydrological, biodiversity, and climate models. Because of the vast area that must be examined, earth observation data offer one of the few viable information sources suitable for global-scale monitoring of forest cover dynamics. Such monitoring has been hindered by data access policies (costs of imagery), inadequate imagery acquisition protocols (few systematic global acquisition strategies), and data processing limitations (methods for processing global data for change monitoring). However, new data streams, freely available imagery, and improved methods now allow operational monitoring of global forest cover change. We present estimates of gross forest cover loss (GFCL) from 2000 to 2005 by using data from two sensor systems appropriate for global-scale inquiry. The global consistency of the methodology allows for comparisons of GFCL among biomes, continents, and countries. A GFCL map is also produced to provide a spatial depiction of primary areas ("hotspots") of GFCL.

Over the past three decades, methods for monitoring forest cover and change over large areas by using satellite data have evolved from the initial work highlighting the dramatic deforestation dynamic of the Brazilian Amazon (1) to the first annual large area deforestation monitoring system, Brazil's National Institute for Space Research PRODES project (2). Other countries have incorporated earth observation data into national monitoring schemes. India, for example, has a similar periodic forest extent and change product to that of Brazil (3). However, synthesizing global forest cover and change from national-scale mapping efforts is not feasible because national capabilities for forest monitoring vary greatly, and the methods and definitions concerning forest cover and extent differ among countries.

Global scale assessments using remotely sensed datasets involve either exhaustive mapping or sample-based approaches. Whereas global mapping at the high spatial resolutions (<50 m) required to adequately quantify forest extent and change may soon be viable, previous efforts employed coarse spatial resolution data sets (4–9) (>250 m), with only one attempting to quantify forest cover change (10). However, coarse resolution data lack sufficient spatial detail to provide reliable area estimates of forest extent and change. Probability-based sampling approaches that use high spatial resolution data have proven to be an effective alternative for quantifying forest extent and change over large areas, and biome-scale studies designed to overcome the varying quality and inconsistencies of national datasets have been implemented (11–13).

Our objective is to provide a global estimate of forest cover extent and GFCL. The methodology is based on a stratified random sample of 541 18.5-km × 18.5-km blocks (a sampling density of 0.22%) and employs data from two satellite-based sensors. Coarse spatial resolution data from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor enable the stratification of the earth's forested biomes into regions of homogeneous forest cover loss. Landsat Enhanced Thematic Mapper Plus (ETM+) data obtained for the sampled blocks were then used to quantify area of year 2000 forest and area of GFCL.

Forest cover is one category of terrestrial land cover. Land cover is the observed physical features, both natural and manmade, that occupy the earth's immediate surface (14). For this study, forest cover is defined as 25% or greater canopy closure at the Landsat pixel scale (30-m × 30-m spatial resolution) for trees >5 m in height. While various canopy closure thresholds are used to define forest cover (12, 15), our definition is based on the ability to identify tall woody vegetation unambiguously in multispectral imagery. For example, the Australian National Carbon Accounting System has employed a 20% threshold due to the fact that Landsat is able to provide consistent mapping of cover and change (16) at or above this canopy density. Our definition of forest having at least 25% cover for trees of at least 5 m in height lends itself more easily to global-scale monitoring from space when using earth observation systems such as Landsat and MODIS.

Human and natural disturbances often lead to changes in land cover, for example, fire converting forest to herbaceous cover. This study focuses on one disturbance dynamic at the global scale, the conversion of forest cover to nonforest cover (GFCL). Areas of GFCL are quantified by using per sample Landsat image pairs consisting of a reference 2000 image for mapping

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[1]To whom correspondence should be addressed. E-mail: matthew.hansen@sdstate.edu.

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forest area and a 2005 image for mapping forest area loss. This globally consistent methodology for quantifying forest cover and GFCL permits comparisons among biomes, continents, and countries (*SI Methods*). Area of forest cover and GFCL for the boreal (17), temperate (18), dry tropics, and humid tropics (19) are presented here as a global synthesis.

The primary source for global information on forest resources to date is the United Nations Food and Agricultural Organization's (FAO) Forest Resource Assessment (FRA) (20). These data, supplied by the contributing member countries, are the current reference for global forest change from 2000 to 2005. However, several features of the FRA data prevent their utility for a global forest change assessment: (*i*) the methods used to quantify forest change are not consistent among all countries, thus hindering the ability to synthesize results; (*ii*) the definition of "forest" is based on land use instead of land cover and the land use definition obscures the biophysical reality of whether tree cover is present; (*iii*) forest area changes are reported only as net values; and (*iv*) forest definitions used in successive reports have changed over time (21). Earth observation datasets can be used to address these limitations by providing globally consistent and spatially explicit characterizations of forest cover extent and change. Such depictions can quantify both forest cover loss and gain independent of land use designations. Plans for the forthcoming FAO FRA 2010 report include a remote sensing survey of forests based on Landsat imagery and a systematic sample of 13,869 10-km × 10-km blocks, representing a sampling density of 1.03% (http://www.fao.org/forestry/fra).

A more recent source of information on forest change is the United Nations Framework Convention on Climate Change (UNFCCC), which tracks national reports on greenhouse gas emissions, including those associated with forest land use and land use change. These national inventories focus on the use of managed lands as a proxy for estimating direct human-induced emissions and removals related to land use. The area changed within forest land use areas is required to estimate emissions and removals, and this information is not available in the FAO FRA reports. Concerning both the FAO FRA and UNFCCC forest monitoring efforts, global-scale remote sensing forest cover change analyses can be of value in (*i*) verifying or confirming reported forest inventories and change and (*ii*) harmonizing data derived from reports that employ different methods or definitions. Inconsistencies in the definitions used and methods applied for forest monitoring at national scales will be unavoidable. Remote sensing data can be used to create an internally consistent global quantification of forest cover change.

This study quantifies a unidirectional change dynamic—GFCL—as a demonstration of the capabilities of remote sensing for global monitoring. Our focus on GFCL is predicated on the premise that Landsat data provide an unambiguous, quantifiable signal of both forest cover and its loss via stand-replacement disturbance. Consequently, we target a feature of the global forest change dynamic, gross loss in forest cover, for which Landsat imagery has a high capacity to detect. Results presented here include forest area and GFCL estimation at biome, continent, and national scales, the latter for each country with forest area >1,000,000 km^2. Data from the study can be viewed and accessed at globalmonitoring.sdstate.edu/projects/gfm. Gross forest cover gain is not quantified and, consequently, net forest cover change dynamics are not reported. Forest cover gain is a more gradual process than forest cover loss and would require adjustments to our methodology. Regional variation in forest land use, natural and human-induced drivers, and forest recovery is significant, and GFCL captures only a part of the global forest cover change dynamic.

Results

Biome-Scale Forest Area and Gross Forest Cover Loss. Forest area for 2000 and GFCL for 2000–2005 are spatially depicted in Fig. 1 *A* and *B* with rates of GFCL summarized in Fig. 2. Global 2000 forest area is estimated to be 32,688,000 km^2 with the humid tropics having the largest forest extent among all biomes (Table 1). The estimated area of GFCL at the global scale is 1,011,000 km^2, representing 3.1% of year 2000 forest area (0.6% per year). GFCL is highest in the boreal forest biome with nearly 60% of the cover lost due to fire (17). The remaining 40% of boreal GFCL is attributable to logging and other change dynamics such as insect and disease-related forest mortality; for example, loss of forest cover in British Columbia, Canada, due to mountain pine beetle infestations (22).

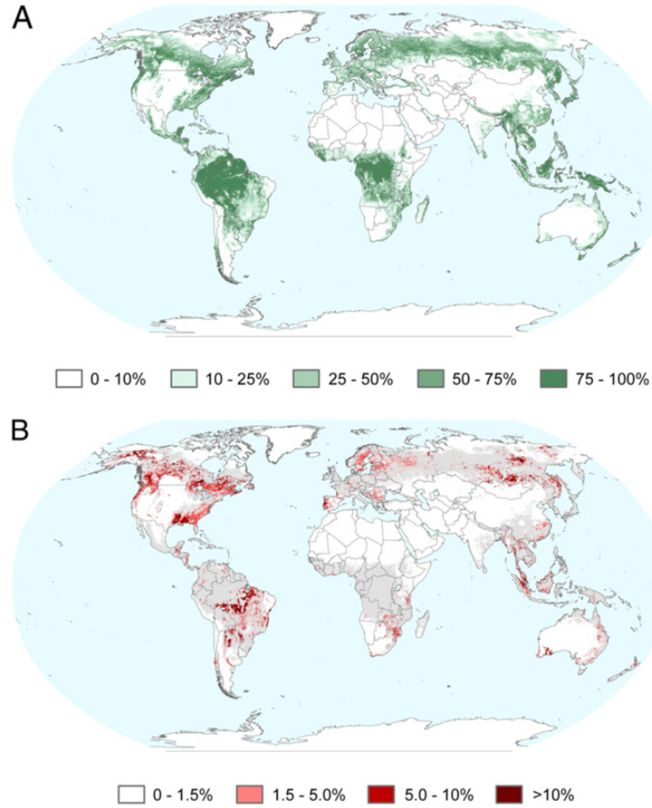

Fig. 1. Estimated percent forest cover, 2000 (*A*) and percent gross forest cover loss (GFCL), 2000–2005 (*B*), both per sample block.

The biome with the second highest area of GFCL is the humid tropics. The majority of this loss is attributable to large-scale agro-industrial clearing in Brazil, resulting in nonforest agricultural land uses, and in western Indonesia and Malaysia, resulting in agro-forestry land uses (19). When GFCL is expressed in terms of the proportion of year 2000 forest, the humid tropical biome is the least disturbed. Large regions of forest absent of large-scale forest disturbance still exist in the humid tropics (Fig. 1). The Amazon interior is the largest remaining intact forest landscape, primarily due to its inaccessibility. The interior Congo Basin also lacks significant forest loss (23, 24). Even though selective logging occurs in many parts of the Congo Basin (25), large-scale agro-industrial clearing is absent.

The dry tropics biome has the third highest estimated area of GFCL. Forests in this biome are predominantly open-canopied and often fire-adapted. The main areas of GFCL in this biome occur in Australia and South America, with Brazil, Argentina, and Paraguay contributing most to South America in the form of agro-industrial scale clearing. The temperate biome has the lowest total area of forest cover of all biomes, as the majority of this biome has long been converted to agricultural and settlement land uses. However, GFCL as a proportion of year

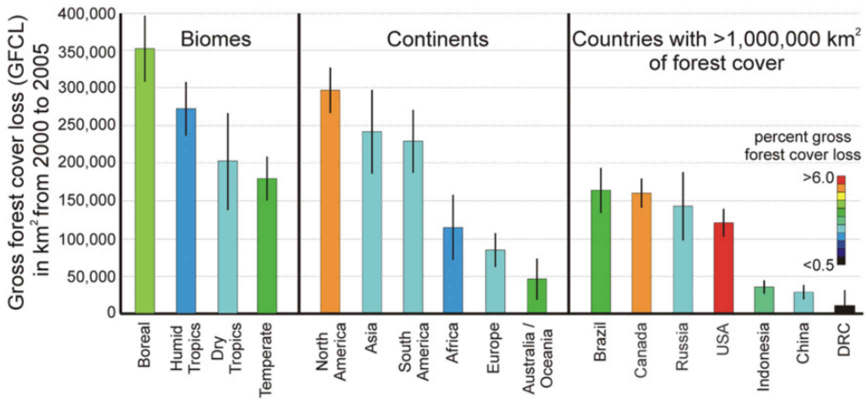

Fig. 2. Estimated gross forest cover loss (GFCL) by biome, continent, and country (error bars represent 95% confidence intervals for area of gross forest cover loss).

2000 forest in the temperate biome is second highest among all biomes. Nearly half of all temperate GFCL is found in North America.

Continental-Scale Forest Area and Gross Forest Cover Loss. Asia and South America are the continents with the largest area of forest cover, each with one-quarter of the global total (Table 2). North America has the greatest area of GFCL, followed by Asia and South America. North America alone accounts for nearly 30% of global GFCL and features the highest proportional GFCL of 5.1%. Africa has the lowest proportional GFCL of 0.4%, reflecting a lower overall use of forests for commercial development. Combined, North and South America account for more than one-half of the global total area of GFCL. South America has the largest remaining intact forests within the tropics (26), areas that are under increasing pressure from agro-industrial development. North America features a spatially pervasive GFCL dynamic with logging and fire as primary causes.

National-Scale Forest Area and Gross Forest Cover Loss. The seven countries exceeding 1,000,000 km^2 in year 2000 forest cover account for 57% of total forest cover and 65% of GFCL during 2000–2005 (Table 3). Russia has the most extensive forest cover, followed by Brazil, Canada, and the United States. Brazil, with significant forest cover in both the humid and dry tropics, has the highest GFCL of any nation. Of the total area of 165,000 km^2 of GFCL from 2000 to 2005 (33,000 km^2 per year), 26,000 km^2 per year is lost within the Brazilian humid tropics and 7,000 km^2 per year within the Brazilian dry tropics. For this time period, our national-scale GFCL area estimate of 33,000 km^2 is close to the FAO FRA estimate of 31,000 km^2 per year (20). Conversely, Brazil's National Institute for Space Research (INPE) reported 111,000 km^2 (2) of tropical deforestation for the Legal Amazon for the 2000–2005 period (22,000 km^2 per year). Our estimate of 165,000 km^2 is higher because our sample represents the entire land surface of Brazil, thus capturing humid tropical GFCL outside of the INPE study area (27) as well as GFCL in the dry tropical cerrado ecoregion. For a product intercomparison of the region common to both our humid tropical biome and the PRODES Legal Amazon forest region, see *SI Methods*. GFCL is found in nearly every region of Brazil, except the interior Amazon and the largely nonforested northeast Caatinga ecoregion and the agricultural south.

Other large tropical forest countries include Indonesia and the Democratic Republic of Congo. Indonesia's GFCL is concentrated in the western Sumatra and Kalimantan island groups. Although Indonesia is considered a nexus of tropical forest cover loss, the GFCL for Indonesia as a proportion of year 2000 forest is estimated to be 3.3%, just above the global estimate of 3.1%. The annualized proportional GFCL for 2000–2005 in Indonesia reflects a reduction in GFCL when compared with estimates of GFCL for 1990–2000 (28). The Democratic Republic of the Congo has the lowest GFCL at 10,000 km^2, or 0.6% of year 2000 forest cover (with the caveat that only seven sample blocks fell in this country). Compared with other more politically and economically stable humid tropical forest regions, Central Africa has a considerably lower rate of GFCL because of less investment in infrastructure and commercial agro-industrial development.

The United States includes temperate and boreal (Alaska) forest cover and has the highest percentage of year 2000 GFCL (6.0%). Although fire is a major contributor, particularly in Alaska and the western part of the country, logging is a primary and widespread cause of GFCL. Regional centers of logging are found mainly in the southeastern states, but also along the west coast and in the upper Midwest. Canada also covers portions of the temperate and boreal biomes, and has substantial GFCL in every province and territory, except Prince Edward Island. The FAO FRA (20) reports 0% net change in Canadian forest area, illustrating the discrepancy in estimates depending on whether forest is defined based on considerations of forest land use or the biophysical presence of tree cover. Our estimate is based on defining forest cover, whereas the FRA estimate is based on a forest land use definition that includes "temporarily unstocked areas, resulting from human intervention or natural causes, which are expected to regenerate" (20). Our estimate of the total GFCL of 160,000 km^2 places Canada a close second to Brazil

Table 1. Biome-scale forest cover and GFCL, 2000–2005, ordered by area of GFCL

Biome	2000 forest cover in km^2	% of total forest cover	2000–2005 GFCL, km^2 (s.e.)	GFCL as % of 2000 forest cover	% of total GFCL
Boreal	8,723,000	26.7	351,000 (22,000)	4.0	34.7
Humid Tropical	11,564,000	35.4	272,000 (17,000)	2.4	27.0
Dry Tropical	7,135,000	21.8	204,000 (32,000)	2.9	20.2
Temperate	5,265,000	16.1	184,000 (15,000)	3.5	18.2
Total	32,687,000	100	1,011,000 (45,000)	3.1	100

Table 2. Continental-scale forest cover and GFCL, 2000–2005, ordered by area of GFCL

Continent	2000 forest cover in km^2	% of total forest cover	2000–2005 GFCL, km^2 (s.e.)	GFCL as % of 2000 forest cover	% of total GFCL
North America	5,829,000	17.8	295,000 (15,000)	5.1	29.2
Asia	8,442,000	25.8	240,000 (28,000)	2.8	23.7
South America	8,414,000	25.7	228,000 (21,000)	2.7	22.6
Africa	5,635,000	17.2	115,000 (21,000)	2.0	11.4
Europe	3,099,000	9.5	86,000 (11,000)	2.8	8.5
Australia/Oceania	1,268,000	3.9	47,000 (13,000)	3.7	4.6
Total	32,687,000	100	1,011,000 (45,000)	3.1	100

(165,000 km^2). Logging predominates in the settled south of Canada, and fire in the largely uninhabited north. Russia has the third highest area of GFCL, but its percent of year 2000 forest cover loss (2.8%) is slightly below the global average. Russia's GFCL is geographically widespread, with logging in the European and far-eastern parts of the country, and fire throughout Siberia (17, 29). Of the seven major forested countries, China is next to the Democratic Republic of Congo in terms of least GFCL. Whereas China's proportional GFCL of year 2000 forest is comparable with Russia's, the overall area of 28,000 km^2 represents only 2.8% of the global total.

For these seven countries with >1,000,000 km^2 of forest cover, Fig. S1 compares the 2000–2005 FRA forest area and net forest area change data (20) with the forest area and GFCL area estimates of this study. Forest area is largely in agreement, except for Russia. Forest area totals for Russia have historically been obscured by complex national definitions (30). Additionally, the application of a 25% canopy cover threshold omits forest area that would be included in many other assessments, including that of the FRA, which employs a 10% cover threshold. Although North America is the site of negligible net change in the FRA report, our estimates depict it as a primary contributor to global GFCL. Similarly, the net gain of forest cover in China from the FRA data does not capture a forest cover loss dynamic of some significance.

Other countries with significant areas of GFCL include Australia, Paraguay, Argentina, and Malaysia (Fig. 1*B*). Fire is the principal cause of forest loss in Australia with significant GFCL in nearly every state. Paraguay continues to have intensive forest clearing related to agricultural development, from the humid tropical Atlantic Interior forests of the east to the dry tropical Chaco woodlands of the west (31). Argentina has a similar dynamic with change in the remaining Atlantic Interior forests of Misiones province, and more widespread clearing of Chaco woodlands in the northwest (32). Malaysia has significant GFCL in every state, largely associated with palm oil expansion and agroforestry.

Discussion

The globally consistent data and methodology used in this study enable direct comparisons of GFCL areas and rates across biomes, continents, and select nations. The inherent inconsistency in previous data collection efforts precluded synoptic, global overview analyses (21). Results augment current global information, namely the FAO FRA data (20), by providing (*i*) gross forest cover loss information, which is not derivable from net change estimates; (*ii*) quantification of the biophysical extent and loss of forest cover, absent of land use considerations, thereby better reflecting the biophysical reality of whether forest cover is present; and (*iii*) improved consistency of forest area and loss data through space and time, enabled by the use of the global remotely sensed data inputs. Results illustrate a globally pervasive GFCL dynamic from 2000 to 2005.

Global variation in GFCL is related to environmental, economic, political, and social factors that determine forest use. Stable political and economic conditions, coupled with access, leads to clearing, a concept consistent with current land cover and land use change theory (33). This simple model of forest clearing has led to the continual reduction of intact forests on every continent (26). The two biomes with largely inaccessible forest regions, the boreal and humid tropics, have comparatively low GFCL when GFCL is expressed as a proportion of year 2000 forest and boreal fires are discounted. Concerning humid tropical forest, mechanisms such as the UNFCCC's REDD (34) initiative aim to reduce tropical deforestation by promoting payments for forest ecosystem services such as carbon storage. Global monitoring of forest cover change will help in evaluating the effectiveness of programs such as REDD.

The often publicized phenomenon of forest conversion within the humid tropics is observed in our results, but significant GFCL is evident in all biomes. For example, rates of GFCL in regions such as the southeast United States are among the highest globally. While many such regions have forest land use designations where forest cover is eventually re-established, the resultant carbon dynamics vary significantly between ecosystems and management regimes. These dynamics are not the same for forest land uses in places as different as Canada and Malaysia.

Table 3. National-scale forest cover and GFCL, 2000–2005, for countries with >1,000,000 km^2 of year 2000 forest cover, ordered by area of GFCL

Country	2000 forest cover in km^2	% of total forest cover	2000–2005 GFCL, km^2 (s.e.)	GFCL as % of 2000 forest cover	% of total GFCL
Brazil	4,601,000	14.1	164,000 (14,000)	3.6	16.3
Canada	3,045,000	9.3	160,000 (10,000)	5.2	15.8
Russian Federation	5,122,000	15.7	144,000 (22,000)	2.8	14.2
United States of America	1,992,000	6.1	120,000 (9,000)	6.0	11.8
Indonesia	1,084,000	3.3	35,000 (4,000)	3.3	3.5
China	1,209,000	3.7	28,000 (5,000)	2.3	2.8
Dem. Rep. of Congo	1,673,000	5.1	10,000 (10,000)	0.6	1.0
Total	18,726,000	57.3	661,000 (30,000)	3.5	65.4

Improved quantification of forest cover change dynamics within areas of designated forest land use are needed, because rates of clearing and recovery are not uniform globally.

The method employed in this analysis was predicated on spectral signatures indicating complete canopy removal. However, the proximate cause of each disturbance was not identified. Only within the boreal biome was forest cover loss due to fire differentiated from forest cover loss in general. Natural forest change processes, such as fire, disease, or storm damage, are sometimes not systematically monitored by forest agencies. However, changing spatiotemporal trends in such disturbances may have significant long-term ecological consequences. Discerning proximate causes of forest loss at the global scale, particularly human-induced clearing versus natural factors, is a valuable line of research inquiry. Such information will be necessary for improved quantification of carbon dynamics. For example, significant aboveground carbon can remain after a fire, such as standing and fallen deadwood (35) in contrast to mechanical harvesting of forest stands.

The capacity for monitoring forest change at the global scale is still being developed. Remote sensing offers an efficient and synoptic method for doing so (36). It is incumbent that such information sources are made available to as wide a user group as possible. This goal is achieved by performing systematic global acquisitions and providing data at no cost with easy access. Systems used in this study, namely MODIS and Landsat, meet these requirements and are the only ones viable for global-scale inquiry. The methodology implemented to estimate GFCL could be applied at finer time scales, for example annually, and at national scales, or within specific subregions, such as unmanaged areas or protected areas. Additionally, it could be modified to estimate gross forest cover gain. Although research on quantifying forest degradation is ongoing (37, 38), operational methods are not ready for implementation at the global scale.

The primary limitation of the sampling method employed in this study is the lack of a fine spatial resolution map product. The block-scale spatial depiction of global GFCL depicts the total area of GFCL as implemented through the regression estimator procedure. However, disaggregation of the change is limited to those areas with a sufficient number of samples to provide estimates of GFCL with small standard errors. For many science applications, spatially explicit map products at finer spatial resolutions are required. For example, exhaustive Landsat-scale resolution mapping has been performed to characterize patterns of forest disturbance and recovery at a continental scale (39), resulting in map outputs appropriate for calibrating carbon cycle models. Spatially explicit global-scale mapping of forest cover dynamics at Landsat-scale will be required for many global change science studies.

Methods

The efficiency of our sampling design was achieved by taking advantage of data from the MODIS sensor to create an effective stratification for forest cover loss. The Landsat ETM+ sensor then provided the primary data for quantifying global GFCL from 2000 to 2005. The probability sampling design was implemented sequentially in four biomes, the humid tropics, boreal, dry tropics, and temperate. Estimates of forest area in 2000 and GFCL area for 2000–2005 were obtained for each biome separately (17–19). The sampling unit was an 18.5-km $\times$ 18.5-km block. Each biome was partitioned into high, medium, and low forest cover loss strata based on MODIS-derived GFCL, with the stratum breakpoints selected independently for each biome (Fig. S2). A stratified random sample of blocks was then selected from each biome, and Landsat imagery was analyzed to quantify forest extent and GFCL per sample block. Example block analyses per biome are shown in Figs. S3 and S4. Stratum-specific regression estimators incorporating MODIS-derived GFCL as the auxiliary variables were applied to generate the mean GFCL estimates. These same estimated regression models were then used to provide a spatial depiction (map) of each biome at the block scale. By construction, the aggregate GFCL portrayed by the map equals the area of GFCL estimated from the sample, thus ensuring internal consistency between the map and estimated area of GFCL. The sample size was sufficient to generate precise estimates of forest cover and GFCL at a continental scale and also at a national scale for those countries containing $>$1,000,000 km^2 of forest cover. Year 2000 forest area estimates were derived separately for each biome by regressing sample block forest area (all pixels $\geq$ 25% canopy closure) against global MODIS Vegetation Continuous Field 2000 data (8).

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