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Global forest area disturbance from fire, insect pests, diseases and severe weather events ☆

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ABSTRACT

Reliable global data on forest degradation and disturbances due to fire, insect pests, diseases and severe weather are important to understand ecosystem health and condition, safeguard production of goods and services and avoid negative impacts on human livelihoods. This paper presents a global analysis of forest area affected by fire, significant insect pest outbreaks, diseases and severe weather reported by countries as part of the Global Forest Resources Assessment 2015. Between 2003 and 2012, approximately 67 million hectares (1.7%) of forest land burned annually, mostly in tropical South America and Africa. In a similar reporting period, in total 142 million hectares of forest land were affected by other disturbances than fire. Insect pests affected more than 85 million hectares of forest, of which a major part was in temperate North America. Severe weather disturbed over 38 million hectares, mostly in Asia. About 12.5 million hectares were reported to be disturbed by diseases, mostly in Asia and Europe. There were strong correlations between burned forest area and the area of partial canopy cover reduction, as well as between burned forest area and net forest loss. Partial canopy cover reduction is used as a proxy for forest degradation, although it also includes land under management that is not degraded. A decreasing trend in burned forest area was found, largely accounted for by decreased area burned within the last ten years in tropical South America. However, an increasing trend in burned forest area was found in the boreal climatic domain. The data on other disturbances was not suitable for determining any year on year correlations and should be improved in future data collection exercises.

1. Introduction

Forest disturbances are the environmental fluctuations and destructive events that disturb forest health and/or structure and/or change the resources or the physical environment at any spatial or temporal scale (FAO, 2005). Disturbances caused by agents such as fire, insect pests, diseases and severe weather are important influences on forest ecosystems.

Under normal circumstances, in healthy forests, disturbances by insect pests and diseases are an integral part of the forest ecosystem (Dajoz, 2000). However, catastrophic disturbances can have undesired impacts on forest ecosystems and can affect environmental functions, with consequences for biodiversity and livelihoods (Schowalter, 2012) and climate change impacts. Cochrane and Barber (2009), for example, describe incidence of catastrophic wildfire in Brazil during the El Niño years of 1997–1998 that destroyed nearly 80% of staple crops within a province. Chambers et al. (2007), using data from moderate spatial resolution satellites, estimated that damage caused to forest land in the United States from hurricane Katrina in 2006 resulted in carbon emissions to the atmosphere of between 50% and 140% the annual net carbon sink of all forests in the country.

Forest disturbance, deforestation due to land use change and climate change are interrelated and compound one another (Dale et al., 2001). Cochrane and Laurence (2008) describe how new deforestation due to land use change in the Amazon can lead to cascading effects including increased flammability of forests, increased burned area and more destructive fires. Climate change could have wide-ranging detrimental effects on the distribution and severity of forest insect and disease outbreaks; Ayres and Lombardero (2000) estimate that in the United States these could result in economic losses of over USD 1 billion annually. Accurate assessment of the size and scope of forest disturbances other than complete overstorey removal is therefore critical for monitoring the Earth's natural systems, especially in the face of a changing global climate (van der Werf et al., 2009).

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To assess the state and trend of forest disturbance globally, the Food and Agriculture Organization of the United Nations (FAO) has sought to aggregate information on forest disturbances in its periodic Global Forest Resources Assessment (FRA). FRA 2000 (FAO, 2001) revealed a lack of national data sources capable of generating global estimates of land and forest area burned. FRA 2005 (FAO, 2007) provided data on global and regional areas burned based on 12 regional working papers prepared within the Global Wildland Fire Network of the United Nations International Strategy for Disaster Reduction (UNISDR). In FRA 2010, FAO attempted to quantify the impacts of many factors that affect the health and vitality of forests by collecting data on the impact of fire together with insect pests and diseases and other biotic and abiotic factors.

Early attempts to assemble global-level information on forest insect pests and diseases included several international meetings held in the 1960s and 1970s (e.g. FAO, 1965, 1976), but since then most of the information available at the global level has been pest specific. As part of FRA 2005, FAO asked countries to report on area affected by insect pests, diseases and other disturbances. This information was supplemented by a thematic study reviewing forest pests in 25 countries (FAO, 2009). In FRA 2010, countries were again asked to report on the impact of insect pests and diseases. However, most countries were unable to provide reliable quantitative information because they did not systematically monitor these disturbances or had limited access to data (FAO, 2011). FRA 2015 responded by modifying the data request to indicate significant outbreaks only. This resulted in more precise reporting of important disturbance than in previous years.

This paper updates the state of knowledge on global forest disturbances from fire, insects, diseases and severe weather. It analyses the status and trend of these various disturbance agents and events as reported by countries for FRA 2015. Total land area burned annually is included, but the analysis and discussion focuses, as much as possible, specifically on disturbed forest area. First presented are the aggregated results of the areal extent of forest disturbances globally, by broad climatic domain and by region. The article describes the trend in burned forest area over time and compares the amount of forest area burned with net deforestation. Further, a new disturbance-related variable in FRA 2015, called partial canopy cover reduction (PCCR), is introduced and analyzed as a proxy indicator of forest degradation. PCCR is summarized by climatic domain and region and related with burned forest area and net forest loss for each.

2. Data and methods

2.1. The Global Forest Resources Assessment

The results presented in this paper are based on data from FRA 2015. FRA relies on responses to a standardized questionnaire submitted by countries through a network of official national correspondents. For the history and details of the FRA reporting process see MacDicken (2015). National correspondents were asked to respond to questions in the following six categories relating to the type, number and areal extent of forest disturbances in their countries: number of fires per year; total land and forest area burned per year; area affected by insect outbreaks; area affected by disease outbreaks; area affected by severe weather events; and area of forest with reduced canopy cover. Where possible, countries were asked to report on specific types of pests, diseases and weather disturbances as well as on the species or forest type affected.

The target reporting years for FRA 2015 were 1990, 2000, 2005, 2010 and 2015. Disturbance variables, however, were not requested specifically for these years because they are by nature episodic. Countries were asked to report annual figures for number of fires and area burned from 2003 to 2012. The area of forest affected by insects, diseases and severe weather was reported non-systematically according to the year the disturbance was detected. The area of forest with reduced canopy cover was calculated on an annual basis, but annual figures were summed to produce a single statistic representing the total area affected between 2000 and 2010.

National reporting of burned area and PCCR was supplemented through the use of remote-sensing data (see Section 2.2). Remote-sensing based values for total burned area, burned forest area and PCCR were provided to the countries as pre-filled variables, and country experts were asked to accept, reject or modify the supplied area estimates with better quality, nationally derived data where available (MacDicken, 2015). This was done in an attempt to make global estimates of burned area more consistent. PCCR was summed for all the years between 2000 and 2012. Thus there is no time series of estimates to determine changes in rates or locations of PCCR.

2.2. Derivation of pre-filled data for burned area

Burned area estimates for FRA 2015 were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 5 Burned Area product (MCD45A1) (Roy et al., 2008) distributed as part of the MODIS fire products suite (Justice et al., 2002). The MODIS sensor is aboard the AQUA and TERRA satellite platforms and is capable of imaging nearly the entire Earth's surface daily with a pixel size of up to 250 m. The algorithm for mapping burned areas is based on the spectral, temporal and structural changes that characterize the land surface after a fire occurs (Roy et al., 2005). It detects the approximate date of burning at 500 m by locating the occurrence of rapid changes over a long time series of daily land-surface reflectance observations.

Estimates of burned forest area were obtained by spatially intersecting the burned area with forest area. Forest areas were determined using Collection 4, Version 3 (Hansen et al., 2006) of the MODIS Vegetation Continuous Fields (VCF) product (MOD44B) (Hansen et al., 2003). The VCF product is a globally consistent depiction of per-pixel percent cover for three types of vegetative cover – woody vegetation, herbaceous vegetation and bare ground – with a pixel size (spatial resolution) of 250×250 m. VCF data have been produced annually since 2000. Forest was distinguished from non-forest by applying a 30% threshold to the continuous VCF values for woody vegetation. Values of less than 30% were considered non-forest, and those of 30% or greater were considered forest. It should be noted that this threshold is different than the 10% used for FRA 2015 and that the MODIS definition of woody vegetation includes areas that are not forest using the FRA forest definition.

2.3. Derivation of pre-filled data for partial canopy cover reduction

Partial canopy cover reduction (PCCR) was defined as a detectable modification of canopy cover, at the 250×250 m MODIS pixel size, that resulted in a partial loss of tree cover relative to a predetermined reference time period, in this case the year 2000. Partial loss was determined on the basis of a change in per-pixel percent tree canopy cover as estimated from the annual VCF time series. Pixels with PCCR between 2000 and 2012 were identified using three main criteria: an initial VCF value greater than 30%; an overall decrease in percent canopy cover greater than 20% between 2000 and 2012; and a negative slope (>-1) of the line formed by the linear regression of the VCF percent tree cover over the period from 2000 to 2012. Pixels where VCF values dropped and stayed

Table 1
Land and forest areas burned globally, 2003–2012.

Year	Burned land (000 ha)	% of land burned	Burned forest (000 ha)	Burned forest as % of burned land	Total forest (000 ha)	% of total forest burned
2003	355 300	2.8	68 592	19.3	4 042 531	1.7
2004	384 798	3.0	75 636	19.7	4 038 801	1.9
2005	369 817	2.9	78 497	21.2	4 035 072	1.9
2006	337 990	2.6	64 250	19.0	4 031 342	1.6
2007	381 897	3.0	84 965	22.2	4 027 613	2.1
2008	322 705	2.5	56 820	17.6	4 023 883	1.4
2009	308 935	2.4	53 728	17.4	4 020 154	1.3
2010	325 229	2.5	65 225	20.1	4 016 424	1.6
2011	322 228	2.5	55 479	17.2	4 012 695	1.4
2012	297 137	2.3	63 141	21.2	4 008 965	1.6
Average	340 604		66 633			

Note: Total land area for all years: 12 908 461 (000 ha). It should be noted that in the case of repeated fires on the same area, it has been accounted for each time.

below the threshold that defines forest (e.g. 10%) were considered deforestation and removed from the analysis. Pixels within the bounds of an intact forest landscape (Potapov et al., 2008) or wetland (Carroll et al., 2009) were also eliminated from the analysis.

2.3.1. Limitations to the method for calculating PCCR

Forest degradation is a term that suffers from many disparate definitions that are often stakeholder dependent (FAO, 2011). Finding a single indicator that serves each of these definitions requires a generic approach. FRA 2015 chose a proxy variable of partial canopy cover reduction (PCCR) to estimate such a proxy. Detecting PCCR from remotely sensed data, especially with the most commonly used forms of medium spatial resolution data, is difficult because forest canopy change almost always takes place at sub-pixel resolution scale when MODIS-sized pixels are used in the analysis. That is to say that the nature of canopy cover change affects areas smaller than the detection capability of the remotely sensed pixel. The methods described here can best be considered a "hot-spot" approach to the detection of partial canopy cover removal.

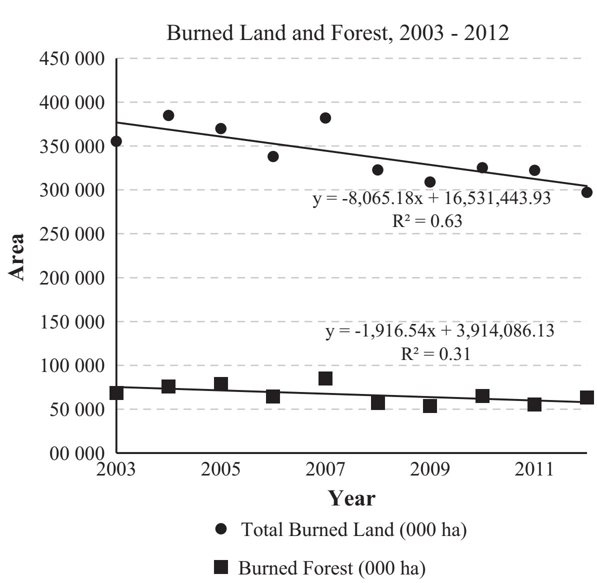

Fig. 1. Total area of burned land and burned forest from 2003 to 2012. The linear trend over time is shown as a solid black line. The equation describing the line and the goodness of fit (R^2) are shown.

Absolute area calculations with MODIS pixels are prone to systematic over- or underestimation, because the MODIS pixel size of 6.25 ha is a limitation to detecting truly fine-scale change. Much change due to PCCR will take place at a scale not detectable by the MODIS pixel unless the change is of a large, diffuse nature. A single MODIS pixel flagged as PCCR can contain either large, diffuse partial canopy cover loss or areas of complete tree cover removal within a matrix of dense tree cover (e.g. smallholder clearing for agriculture in an otherwise forested pixel). These clearings, at a finer scale of analysis, may meet the definition of deforestation. Researchers are currently exploring the potential of high spatial resolution satellite data for measuring and monitoring forest degradation, but this effort is largely in its early phases (Gascon and Eva, 2014; GFOI, 2013).

2.4. Analysis of variables

The areal extent of forest disturbances was summarized globally and by smaller geographic region including climatic domain, geographic region and income category. Climatic domains were delineated into four global ecological zones: boreal, temperate, subtropical and tropical (FAO, 2012; MacDicken, 2015). If a country's national boundaries, as defined by the Global Administrative Unit Layers (GAUL) (FAO, 2008), encompassed more than one climatic domain, the country was assigned to the domain occupied by the largest part of the country's forest area. Countries were also divided into five regions defined in the FRA process and into low, medium–low, medium–high and high-income categories according to the World Bank income-group classification. Income categories are defined by gross national income per capita per year: low (USD 1045 or less), lower middle (USD 1046–4125), upper middle (USD 4126–12 745) and high (USD 12 746 or more) (MacDicken, 2015).

2.5. Missing data

A few very large forested countries (Australia, Brazil and India) did not provide annual estimates of burned area for all years. Without these countries included, the burned area analysis would be incomplete for the purposes of this paper. Accordingly, data for the missing years were imputed from the available values in the annual records of these countries. The area of burned forest for missing years was calculated using the average percentage forest burned obtained from the data reported by the country.

Brazil reported burned area directly for 2005–2010. The burned area reported by Brazil was between 3 and 16 times greater than the MODIS burned area product. The reason for this discrepancy is not known; it may be attributable to a large burned area under dense tree canopy which may go undetected by the MODIS burned area algorithm (Giglio et al., 2006). The reported burned area, however, exhibited a high correlation ($R^2 = 0.71$) with the number of fires detected by the MODIS sensor and published by the Instituto Nacional de Pesquisas Espaciais (INPE, 2015). The burned area for the years that were not reported directly were imputed by using the equation formed by the linear regression of number of fires and burned area for the years directly reported.

Australia reported burned area annually for 2006–2011. The reported burned area exhibited a very high correlation ($R^2 = 0.99$) with the MODIS-derived pre-filled values for those years. Thus, the FRA pre-filled values were used for the years not directly reported by Australia.

India supplied no burned area values for any years in its report to FRA 2015. Values for India's annual burned land and forest area were taken directly from the FRA pre-filled values as these were the best available information.

Table 2
Forest area, burned forest and proportion burned forest by climatic domain, 2003–2012.

Year	Tropical			Subtropical			Temperate			Boreal		
	Forest area (000 ha)	Burned forest (000 ha)	% of forest burned	Forest area (000 ha)	Burned forest (000 ha)	% of forest burned	Forest area (000 ha)	Burned forest (000 ha)	% of forest burned	Forest area (000 ha)	Burned forest (000 ha)	% of forest burned
2003	1 854 869	57 577	3	324 237	4949	2	648 037	2235	0.3	1 219 710	4056	0.3
2004	1 847 336	59 509	3	323 807	8556	3	651 328	3874	0.6	1 220 168	3729	0.3
2005	1 830 799	67 753	4	323 912	4248	1	659 176	4140	0.6	1 218 855	2519	0.2
2006	1 832 271	44 877	2	322 949	8854	3	657 910	6682	1.0	1 221 084	3760	0.3
2007	1 824 739	71 138	4	322 519	6913	2	661 200	4303	0.7	1 221 542	2582	0.2
2008	1 817 206	44 729	2	322 090	6041	2	664 491	2204	0.3	1 222 000	3800	0.3
2009	1 809 674	36 278	2	321 660	10 545	3	667 782	3966	0.6	1 222 458	2895	0.2
2010	1 797 758	56 045	3	319 613	2751	1	673 429	1361	0.2	1 224 873	5084	0.4
2011	1 794 609	42 547	2	320 802	8752	3	674 364	2060	0.3	1 223 374	3844	0.3
2012	1 787 077	50 655	3	320 372	8045	3	677 655	2115	0.3	1 223 832	4106	0.3

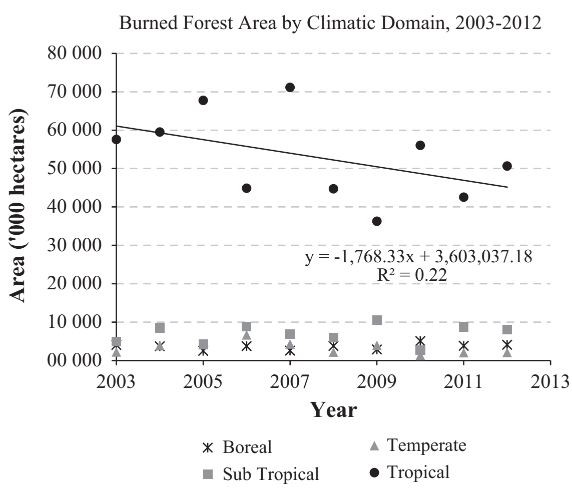

Fig. 2. Annual burned forest area by climatic domain, 2003–2012. The linear trend over time is shown for the tropical domain as a solid black line. The equation describing the line and the goodness of fit (R^2) are shown.

Annual forest area figures used in burned area analyses were taken from Keenan et al. (2015) for the nominal FRA reporting years. Forest area for years not reported in FRA was imputed linearly and separately at the global, regional and climatic domain levels. These are the best estimates available for the missing years; however, they will not sum correctly and are subject to rounding.

Significance of the trend in burned forest area over time was assessed using the Mann–Kendall test for monotonic trend in time-series data. Significance was tested at each level of aggregation twice, once with raw data and a second time with values smoothed by applying a moving average. Statistical tests were performed using the statistical software R (R Core Team, 2014) and the 'rkt' package (Marchetto, 2015).

The availability of quantitative data for insect pests, diseases and severe weather events was limited – although this can indicate either a lack of data or a lack of significant disturbance. The aggregated data on insect pests, diseases and severe weather events are based on latest occurrence so they refer to different reporting years and sometimes to multiple years (e.g. intervals). Thus it was only possible to summarize all incidences, for any year and for any kind of insect pest, diseases or severe weather event.

3. Results

3.1. Countries reporting

In total, 155 country reports were examined for disturbance from fire, pests, disease and severe weather. Of these, over 140 countries, representing >90% of the total land area and >99% of the world's total forest area, reported burned area.

Only 75 countries reported on the areal extent of disturbances from insect pests, diseases or severe weather. In total, these 75 countries represented 70% of the total global forest area. PCCR values of >0 were found in 133 countries and territories, of which 29% were desk studies and were not subject to review by national authorities.

3.2. Land area and forest area burned

3.2.1. Land area and forest area burned globally

The results over the ten-year period from 2003 to 2012 indicate that an average of 341 million hectares, or 2.6% of all land area, was burned annually (Table 1). This is in line with the estimate by Chatenoux and Peduzzi (2013) of 327 million to 391 million hectares per year from 2000 to 2011 based on SPOT (Satellite Pour l'Observation de la Terre) Vegetation satellite sensors and MODIS; the 350 million hectares estimated for the year 2000 by the Joint Research Centre of the European Commission, based on MODIS products (JRC, 2005); and the estimate by Roy et al. (2008) of 280 million to 290 million hectares for the first consecutive 12 months (2001–2002) of the MODIS global burned area product.

In the same time period, an average of about 67 million hectares or 1.7% of forest land burned each year (Table 1). About 20% of all area burned annually was in forests as compared with 80% outside forests.

Total land area burned over the 10 years analyzed in this paper exhibits a variable but decreasing trend (Fig. 1). This result is similar to findings reported by Giglio et al. (2010), who used a combination of moderate and coarse resolution satellite imagery sources to analyze trends and variability in burned area globally from 1996 to 2009. The amount of forest area burned is also decreasing annually, but at a lesser rate than total land area.

3.2.2. Land area and forest area burned by climatic domain

By climatic domain, the largest area of land and forest burned was in the tropics, where more than 290 million hectares of land burned annually (between 79% and 91% of total global burned area). Of the total area burned in the tropics, over 53 million hectares were in forest land (Table 2). In the subtropical domain, nearly 33 million hectares of land burned each year, of which approximately 7 million hectares were forest land. The temperate and boreal domains accounted for nearly 15 million hectares of land burned, of which approximately 7 million hectares were forest land.

The highest proportion of forest area burned was also in the tropics, where almost 3% of forest burned annually during the

Table 3
Forest area, burned forest and proportion burned forest by region, 2003–2012.

Year	Africa			Asia			Europe			North and Central America			Oceania			South America		
	Forest area (000 ha)	Burned forest (000 ha)	% of forest burned	Forest area (000 ha)	Burned forest (000 ha)	% of forest burned	Forest area (000 ha)	Burned forest (000 ha)	% of forest burned	Forest area (000 ha)	Burned forest (000 ha)	% of forest burned	Forest area (000 ha)	Burned forest (000 ha)	% of forest burned	Forest area (000 ha)	Burned forest (000 ha)	% of forest burned
2003	660 827	18 658	3	574 207	1093	0.2	1 004 469	3039	0.6	748 586	3660	0.5	186 428	4177	2	878 054	38 190	4
2004	657 723	16 321	2	576 025	1342	0.2	1 005 448	1251	0.1	748 758	6365	0.9	186 091	8270	4	874 796	42 120	5
2005	654 679	15 449	2	580 868	2813	0.5	1 004 147	1727	0.2	747 953	5450	0.7	176 485	3436	2	868 611	49 785	6
2006	651 515	18 383	3	579 660	1279	0.2	1 007 407	4207	0.4	749 102	6038	0.8	185 418	8472	5	868 280	25 794	3
2007	648 411	21 205	3	581 478	2216	0.4	1 008 386	2080	0.2	749 274	5013	0.7	185 081	6663	4	865 022	47 758	6
2008	645 307	17 186	3	583 296	2270	0.4	1 009 365	2595	0.3	749 446	3415	0.5	184 745	5826	3	861 764	25 484	3
2009	642 203	14 503	2	585 114	1078	0.2	1 010 345	3975	0.4	749 618	2970	0.4	184 408	10 236	6	858 506	20 921	2
2010	638 282	18 986	3	589 406	1377	0.2	1 013 572	2614	0.3	750 278	3892	0.5	172 002	2557	1	852 133	35 815	4
2011	635 995	14 929	2	588 749	0502	0.1	1 012 303	1710	0.2	749 963	4324	0.6	183 735	8494	5	851 990	27 243	3
2012	632 891	14 290	2	590 567	0612	0.1	1 013 283	2659	0.3	750 135	3833	0.5	183 398	7679	4	848 732	35 848	4

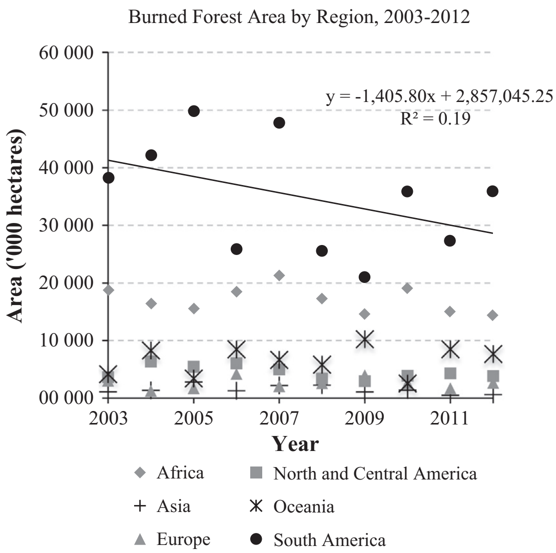

Fig. 3. Annual burned forest area by region, 2003–2012. The linear trend over time is shown for South America as a solid black line. The equation describing the line and the goodness of fit (R^2) are shown.

period (Table 2). At the same time 2% of subtropical forests burned annually and less than 1% of temperate and boreal forests. The tropical domain shows a decreasing trend in forest area burned. The subtropical, temperate and boreal domains, however, do not show any definite trend (Fig. 2).

3.2.3. Land and forest burned by region

The largest area of land burned was in Africa: over 213 million hectares annually. Of this amount, nearly 17 million hectares of forest land burned each year (Table 3). In South America, an average of 72 million hectares of land area burned each year, of which 35 million hectares were forest land. Oceania reported 31 million hectares of land burned annually, of which approximately 7 million hectares were forest land. Asia had approximately 17 million hectares of burned land per year, of which less than 2 million hectares were forest land. Nearly all of the land burned in North and Central America (total 5 million hectares) and Europe (total 3 million hectares) was forest land.

At the regional level, annual burned forest area was variable. However, a few regions show signs of a noticeable trend. A definite decreasing trend in forest area burned is noticeable in South America (Fig. 3). A slight decreasing trend in forest area burned is detectable in Africa. Other regions show no clear trend in burned forest area.

3.2.4. Land and forest area burned by income category

The largest area of land and forest burned annually was in countries in the upper-middle income category, 123 million hectares and 40 million hectares, respectively (Table 4). The low-income countries had the next largest area of land burned annually, or 101 million hectares, but a smaller proportion was forest land, approximately 11 million hectares. High-income countries reported 38 million hectares of land burned annually, of which approximately 13 million hectares were forest land.

High-income and low-income countries on average had similar amounts of forest area burned. However, the low-income countries have far less forest area (Keenan et al., 2015), so they have a much higher proportion of their forest area burned, and non-forest land constitutes a far greater proportion of area burned in low-income countries than in high-income countries (90% versus 61%).

Decreasing trends in forest area burned are observed in nearly all income categories, with the strongest seen in the upper middle-income category (Fig. 4). Low and lower middle-income categories showed slight decreasing trends in forest area burned as well. The high-income category did not exhibit a strong trend.

3.2.5. Significance of trends in burned area and burned forest area

To assess the significance of the trend in burned area and burned forest area over time, the Mann–Kendall test for monotonic trend in time-series data was applied at each aggregation level. When all observations were considered independently, the tropical domain exhibited a significantly negative trend in total burned land area. The African region also exhibited a significantly negative trend in total burned land area. No climatic domain or region exhibited a significant trend in burned forest area. By income group, lower-middle and lower income groups showed significantly decreasing trends in total land area burned. No income group had significant trends, positive or negative, in burned forest area (Table 5).

Trends in burned land and burned forest area were examined a second time, but with moving averages applied at 3 or 4-year intervals to smooth the trend over time. When the Mann–Kendall test was applied to these data, significant declines in total area burned were again found in the tropical domain but also in the temperate domain. Regional total area burned significantly decreased in Africa, Asia and South America. Burned forest area exhibited significant declines in the tropical and temperate domains and a significant increase in the boreal domain. Only South America exhibited a significant trend, declining, in forest area burned at the regional level. By income group, the upper-middle, lower-middle and lower groups exhibited a significant decreasing trend in total land area burned. Only the upper-middle income group showed a significant trend, decreasing, in forest area burned (Table 5).

Table 4
Forest area, burned forest and proportion of forest burned by income category, 2003–2012.

Year	High			Upper middle			Lower middle			Low		
	Forest area (000 ha)	Burned forest (000 ha)	% of forest burned	Forest area (000 ha)	Burned forest (000 ha)	% of forest burned	Forest area (000 ha)	Burned forest (000 ha)	% of forest burned	Forest area (000 ha)	Burned forest (000 ha)	% of forest burned
2003	1 818 541	10 642	0.6	1 233 967	43 510	4	553 186	3462	0.6	427 711	11 203	3
2004	1 819 480	15 355	0.8	1 233 363	45 382	4	551 598	4209	0.8	425 240	10 722	3
2005	1 817 957	10 174	0.6	1 231 708	53 862	4	550 997	5365	1.0	422 921	9260	2
2006	1 821 357	16 112	0.9	1 232 153	31 726	3	548 423	4745	0.9	420 297	11 591	3
2007	1 822 295	12 826	0.7	1 231 548	52 774	4	546 836	5001	0.9	417 825	14 334	3
2008	1 823 233	11 340	0.6	1 230 943	29 982	2	545 248	5977	1.1	415 354	9476	2
2009	1 824 172	15 432	0.8	1 230 338	26 929	2	543 661	2533	0.5	412 882	8789	2
2010	1 825 524	8608	0.5	1 228 041	40 174	3	542 767	4088	0.8	410 211	12 368	3
2011	1 826 049	12 534	0.7	1 229 128	31 526	3	540 486	2395	0.4	407 939	8987	2
2012	1 826 987	12 122	0.7	1 228 523	39 808	3	538 898	2640	0.5	405 468	8585	2

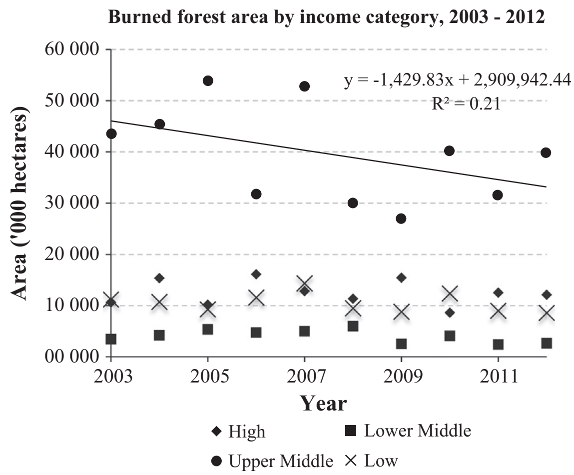

Fig. 4. Annual burned forest area by income category, 2003–2012. The linear trend over time is shown for upper-middle income category as a solid black line. The equation describing the line and the goodness of fit (R^2) are shown.

3.3. Forest area affected by other disturbances

In the 75 countries that reported on insect pests, diseases and severe weather events, the total forest area affected by these disturbances, over all years reported, was 141.6 million hectares. This represents 5% of the total forest area in these countries (2807 million hectares). Insect pests accounted for the greatest part of the area damaged, followed by severe weather events (Table 6). However, many factors limit the ability to report on forest damaged by disease, including the nature of disease cycles, spatial distribution of pathogens and complexities in assessment of disease in standing trees (Burdon, 1987; Sturrock et al., 2011). As a result, reported disease damage may be underestimated.

3.3.1. Forest area affected by other disturbances by climatic domain

Temperate forests accounted for the largest area of forest reported damaged by insect pests, 69.6 million hectares (Table 6). Recent outbreaks of bark beetles in North America (Hicke et al., 2012; Walton, 2013) appear to have been the biggest contributor to temperate forest damage.

3.3.2. Total forest area affected by other disturbances by region

Insect pests were the leading cause of forest disturbance other than fire in nearly all geographic regions. In North America, they are the leading cause of forest disturbance. North America reported the largest area of forest disturbed by insect pests, 57 million hectares (Table 7), again demonstrating the continuing significance of damage by bark beetles (Walton, 2013). African countries reported over 9 million hectares of forest damaged by insect pests.

Severe weather events were the leading cause of reported forest disturbance other than fire in Asia. Nearly 18 million hectares of forest were damaged by severe weather in this region. North and Central America reported over 13 million hectares of forest damaged by severe weather.

Diseases affected a relatively small extent of forests in all geographic regions. Asia reported over 5 million hectares of forest affected by diseases, and Europe reported just under 5 million hectares affected.

3.4. Partial canopy cover reduction

3.4.1. Total forest area exhibiting PCCR by climatic domain

The tropical domain was the climatic domain with the most PCCR detected, over 156 million hectares or 9% of the domain's forest area as reported in 2010 (Table 8), as compared with 1–2% in the other domains.

The study found a strong linear correlation between PCCR and net deforestation by climatic zone ($r^2 = 0.92$).

3.4.2. PCCR by region

Asia was the region with the highest amount of indicated PCCR, almost 54 million hectares. Africa was next, followed by South America (Table 9).

The study found a strong linear correlation between PCCR and net deforestation by region (excluding Asia) ($r^2 = 0.83$).

4. Discussion

Forest disturbance covers phenomena that, in most cases, do not necessarily cause conversion of forest land to other land uses. It is important to measure and monitor these disturbances as they are important indicators of ecosystem health, have a large impact

Table 5
Significance of trend (columns 1–4) and smoothed trend (columns 5–10) in total land area and forest area burned between 2003 and 2012 by climatic domain, region and income group. The sign (+/−) indicates the direction of the slope of the line formed by burned area over time. Significance ($p < 0.05$) of the trend as determined from the Mann–Kendall test is indicated as (n.s.) if no significance and (*) if significant. Column 'Avg' indicates the number of years included in the moving average to smooth the trend.

Aggregation	Trend burned area	$p < 0.05$	Trend burned forest area	$p < 0.05$	Trend burned area, smoothed	Avg	$p < 0.05$	Trend burned forest area, smoothed	Avg	$p < 0.05$
Climatic domain										
Tropical	−	*	−	n.s.	−	3	*	−	3	*
Subtropical	+	n.s.	+	n.s.	+	3	n.s.	+	3	n.s.
Temperate	−	n.s.	−	n.s.	−	3	*	−	4	*
Boreal	+	n.s.	+	n.s.	+	3	n.s.	+	4	*
Region										
Africa	−	*	−	n.s.	−	3	*	−	3	n.s.
Asia	−	n.s.	−	n.s.	−	3	*	−	3	n.s.
Europe	+	n.s.	+	n.s.	+	3	n.s.	+	3	n.s.
North and Central America	−	n.s.	−	n.s.	−	3	n.s.	−	3	n.s.
Oceania	+	n.s.	+	n.s.	+	3	n.s.	+	3	n.s.
South America	−	n.s.	−	n.s.	−	3	*	−	3	*
Income group										
High	+	n.s.	−	n.s.	+	3	n.s.	−	3	n.s.
Upper middle	−	n.s.	−	n.s.	−	3	*	−	3	*
Lower middle	−	*	−	n.s.	−	3	*	−	3	n.s.
Low	−	*	−	n.s.	−	3	*	−	3	n.s.

Table 6
Forest area affected by other disturbances by climatic domain as reported to FRA 2015.

Climatic domain	Forest area affected (000 ha)				
	Insect pests	Disease	Severe weather	Unknown	Total
Boreal	3702	3165	3397	4657	14 920
Temperate	69 582	3034	32 251	117	104 983
Subtropical	2619	5195	37	343	8194
Tropical	9616	1060	2749	42	13 467
Total	85 518	12 454	38 433	5158	141 564

on the delivery of forest ecosystem services and may not be readily reported in deforestation statistics.

Forest disturbances also interact. Veblen et al. (1994) found that in a subalpine forest severe snow avalanches influenced the spread of wildfires and young *Picea* sp. populations did not support a spruce beetle attack following devastating fire or avalanche. Also for a subalpine forest, Buma and Wessman (2011) investigated a gradient of disturbance interaction severities and found that windstorms in 1997 followed by wildfire in 2002 created novel conditions that exceeded the resilience of the ecosystem, leading to the absence of regeneration eight year post fire in areas were fire came after medium to high severity blowdown. For this paper however, the interaction of disturbances could not be analyzed.

4.1. Burned area

The results of this study indicate that annual burned forest area is highest in the tropics. Burning of forests in the tropics is of great concern, as tropical forests are home to over one-half the biological diversity on Earth (Lewis, 2006), support the livelihoods and well-being of hundreds of millions of people (Dawson et al., 2014), are extremely important for maintaining local, regional and even global weather and climate (Avissar and Werth, 2005; Spracklen et al., 2012) and are large carbon sinks (Pan et al., 2011).

A very strong exponential relationship was found between the total forest area burned and total net forest loss at the regional and climatic domain levels ($R^2 = 0.96$ and 0.95, respectively). Though there are few data points, it is likely that burning of forests is the precursor to forest conversion, especially in the tropics where slash-and-burn agricultural practices are common (Lambin et al., 2003; Carmenta et al., 2011). Alencar et al. (2011) determined that nearly 23% of burned area in a portion of the Amazon forest was ultimately converted to a different land use. Gibbs et al. (2010) showed that tropical forest land, both primary and secondary, comprised 83% of all global agricultural expansion between 1980 and 2000 and predicted that this proportion would remain high with rising demand for meat and grains. Brink and Eva (2009), through analysis of a 25-year time-series of satellite imagery, determined that agriculture increased by 57% in sub-Saharan Africa from 1975 to 2000, largely in previously forested landscapes.

The results presented in this paper indicate a decreasing trend in burned area and burned forest area globally. This was most notable in the tropical domain and in the South American region. The decrease in burned area in the tropics is corroborated by other recent studies (Yang et al., 2014; Giglio et al., 2010). Yang et al. (2014) noted that decreasing forest conversion to pasture and increasing forest conversion to cropland and mechanized agriculture – as observed by Morton et al. (2006) in the Brazilian Amazon – may contribute to the decrease in burned forest area in tropical South America because pastureland is prone to larger and more frequent fires than cropland. Not only is less burning required for conversion, but repeat burning is also reduced. Gregoire et al. (2012) found, similarly, that conversion of land to cropland in Africa has the effect of decreasing the amount of burned area detected in that region.

The decreasing trend in forest area burned is also visible in the upper middle-income category. Brazil is a large forested country within this income category, which suggests again that activities in Brazil may be affecting the total status and trend in forest disturbance for the tropical domain.

There was a significantly increasing trend in burned forest area in the boreal climatic domain, when considering the smoothed trend line. Kasischke and Turetsky (2006) found an increasing trend in burned area, larger fire years and increased lightning ignitions in the boreal zone of North America from the 1960's to 1999. Oris et al. (2013) suggest that increased burning in the boreal zone was predicted as a result of a warming global climate and could have positive feedbacks on boreal area burned.

4.2. Insect pests, diseases and severe weather

Fire is clearly one of the most dominant forces affecting the Earth's land surface. However, on forest land insect pests, diseases and severe weather are also significant disturbance agents. For example, Dale et al. (2001) found that in the temperate forests of North America insect pests and diseases affected almost 50 times as much forest as burning annually. Logan et al. (2003) corroborated the large-scale impacts of insect pests and diseases on forest land in North America and indicated that most global climate change scenarios favor the increased incidence of outbreaks in temperate forests in the future.

The data available from FRA 2015 do not allow for year on year comparison of the relative amounts of forest affected by burning and other disturbances. Complexities associated with assessing the areas affected by these disturbances limit countries' ability to report in this category and in many cases there are no severe disturbance events to report. Forest disturbances and diebacks are often associated with a broad range of interrelated biotic and abiotic causative agents, and multi-scale monitoring approaches are required to quantify their impacts (Michaelian et al., 2011). Such

Table 7
Forest area affected by other disturbances by region as reported to FRA 2015.

Region	Forest area[a] (000 ha)	Forest area disturbed (000 ha)					% of forest area disturbed
		Insect pests	Diseases	Weather	Unknown	Total	
Africa	104 392	9518	1042	2563	5	13 128	12.6
Asia	399 796	7406	5251	17 814	307	30 778	7.7
Europe	941 992	10 449	4681	4963	4774	24 867	2.6
North and Central America	738 287	57 024	1260	13 087	61	71 432	9.7
Oceania	10 158	2	196	6	0	204	2
South America	612 358	1120	24	0	12	1156	0.2
Total	2 806 983	85 519	12 454	38 433	5159	141 564	5.0

[a] Aggregated 2010 forest area of the countries that reported on these disturbances to FRA 2015.

Table 8
Partial canopy cover reduction (PCCR) area by climatic domain, sum for 2000–2010. Proportion of total 2010 forest area.

Climatic domain	Total forest area, 2010 (000 ha)	PCCR (000 ha)	PCCR as % of total forest area 2010
Tropical	1 797 758	156 549	8.7
Sub-tropical	319 613	6751	2.1
Temperate	673 429	6010	0.9
Boreal	1 224 873	15 819	1.3
Total	4 015 673	185 129	4.6

complete surveys are rare, so the quantifiable impact on forest cover by insect pests and diseases is often underestimated. Assessment methods were not reported to FRA, but are likely to vary among countries, domain and region and are affected by vegetation assemblages and climate.

The analysis by climatic domain and region must be interpreted with caution, as these figures are influenced by the number of reporting countries. The global area damaged by insect pests, diseases and severe weather events overall is expected to be higher than reported.

4.3. Forest degradation

Forest degradation is an important, yet difficult parameter to measure. It is important because it affects forest productivity, biodiversity and atmospheric carbon flux can be a precursor to forest loss. Over the period 1991–2015 deforestation is estimated a net emission source (4.04 Gt CO_2 yr^{-1}) and forest degradation is estimated at about one fourth (0.8 Gt CO_2 yr^{-1}) of this (Federici et al., 2015). Locally, degradation rates can be equal to, or in some cases as much as double, the rates of true deforestation (Zhuravleva et al., 2013).

Measuring forest degradation is problematic in part because it is difficult to define and often difficult to separate from any form of forest management, whether sustainable or not. Lund (2014) lists more than 50 different definitions of forest degradation, with determinant characteristics ranging from biophysical alteration to biodiversity reduction and reduced ability to provide ecosystem services. Degradation *per se* was not measured in FRA 2015, rather PCCR was used as a proxy.

This study found a strong linear correlation between PCCR and net forest loss by region (excluding Asia) and climatic zone (R^2 = 0.83 and 0.92, respectively). This indicates that, generally speaking, where forest loss rates are highest so too is the rate of partial canopy cover loss, or degradation. Because forest conversion usually occurs in areas proximal to existing cleared areas, it is likely that much of the detected PCCR will ultimately convert to forest loss. Margono et al. (2012) found that almost 97% of new deforestation on the island of Sumatra occurred in previously disturbed or degraded forests.

Table 9
Partial canopy cover reduction (PCCR) by region, sum for 2000–2010.

Region	Total forest area, 2010 (000 ha)	PCCR (000 ha)	PCCR as % of total forest area 2010
Africa	638 282	50 337	7.9
Asia	589 406	53 859	9.1
Europe	1 013 572	17 911	1.8
North and Central America	750 278	10 379	1.4
Oceania	172 002	5443	3.2
South America	852 133	47 198	5.5
Total	4 015 673	185 127	4.6

The results of this study also indicate a moderate linear correlation between total burned forest area and PCCR (R^2 = 0.67) at the regional level (excluding Asia). Thus, fire is a likely contributor to forest degradation in most subregions.

Satellite imagery analysis of PCCR does not indicate the cause of canopy cover reduction, which could include anthropogenic actions which may be considered harmful to the functioning of intact forests as well as human management activity and natural causes that are part of properly functioning forest ecosystems or could be considered enhancements to forest systems. It is certain that some areas where canopy cover is reduced are actually managed sustainably. Unfortunately, no suitable data were available to test this relationship.

Finally, this paper does not consider the type of forest area – primary, natural or planted, as reported in FRA 2015 – affected by disturbance. It is likely that most of the results and discussion presented here refer largely to natural forest and not planted forest areas.

5. Conclusion

This paper analyzed data reported by countries for FRA 2015 on forest disturbance from fire, insect pests, diseases and severe weather globally, by climatic domain and by region. Over the ten-year period from 2003 to 2012, an average of over 50 million hectares of forest land burned each year, representing 1.4% of all forest area and 16% of all land area burned. Burned area was well correlated with net forest loss and forest degradation at the climatic zone and regional levels. A variable but decreasing trend in burned forest area was detected, especially in the tropics and particularly in South America. South America was the region that accounted for the largest proportion of forests burned, nearly 40%. Forest area burned annually was similar for high and low income categories, but since low income countries have far less forest land, a higher proportion of their forest was affected by fires.

Over a similar time period countries reported nearly 142 million hectares of forest affected by other disturbances, including 85 million hectares affected by insect pests and over 38 million hectares by severe weather events. Of the total, more than 104 million hectares were affected in temperate countries; the bark beetle outbreak in North America was a major contributor.

It is important to provide information that may assist in the quantification of forest disturbance and degradation where it is occurring, despite difficulties in defining, detecting, measuring and monitoring. This is especially critical with changing climatic conditions, under which many biotic and abiotic disturbances are expected to alter in intensity, quantity and frequency, with consequences for forests in many parts of the world.

The availability of country-level information on disturbances is still relatively poor. More complete information on fire, insect pests, diseases and severe weather events could make it possible to answer important questions, e.g. how does forest canopy cover loss vary with the rates of natural phenomena such as fires, insect pests and diseases? How does the incidence of severe weather conditions such as drought affect the incidence of insect pests and diseases? How does the management of one type of disturbance ameliorate or exacerbate the impact of associated disturbances?

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