Erratum: Trends in size of tropical deforestation events signal increasing dominance of industrial-scale drivers (2017 Environ. Res. Lett. 5 054009)

Kemen G Austin¹, Mariano González-Roglich¹ ², Danica Schaffer-Smith¹, Amanda M Schwantes¹ ³ and Jennifer J Swenson¹

¹ Duke University, Nicholas School of the Environment, Box 90328, Durham, NC 27708, United States of America
² Current affiliation: Moore Center for Science, Conservation International, 2011 Crystal Drive, Suite 500, Arlington, VA 22202, United States of America
³ Author to whom any correspondence should be addressed. E-mail: amanda.schwantes@duke.edu

The label in figure 2(a) should correctly read ‘Change in the rate of deforestation (kha yr⁻¹)’. In the results section (lines 6–10), the sentence should correctly read ‘Deforestation increased significantly in 37 countries, led by Indonesia, Malaysia, Bolivia, Cambodia, Paraguay, and Myanmar (Burma) where deforestation rates increased >10 000 ha yr⁻¹ (figure 2(a)).’
Trends in size of tropical deforestation events signal increasing dominance of industrial-scale drivers

Kemen G Austin¹, Mariano González-Roglich¹,², Danica Schaffer-Smith¹, Amanda M Schwantes¹ and Jennifer J Swenson¹,³

¹ Duke University, Nicholas School of the Environment, Box 90328, Durham, NC 27708, United States of America
² Current affiliation: Moore Center for Science, Conservation International, 2011 Crystal Drive, Suite 500, Arlington, VA 22202, United States of America
³ Author to whom any correspondence should be addressed.
E-mail: jswenson@duke.edu

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Abstract
Deforestation continues across the tropics at alarming rates, with repercussions for ecosystem processes, carbon storage and long term sustainability. Taking advantage of recent fine-scale measurement of deforestation, this analysis aims to improve our understanding of the scale of deforestation drivers in the tropics. We examined trends in forest clearings of different sizes from 2000–2012 by country, region and development level. As tropical deforestation increased from approximately 6900 kha yr⁻¹ in the first half of the study period, to >7900 kha yr⁻¹ in the second half of the study period, >50% of this increase was attributable to the proliferation of medium and large clearings (>10 ha). This trend was most pronounced in Southeast Asia and in South America. Outside of Brazil >60% of the observed increase in deforestation in South America was due to an upsurge in medium- and large-scale clearings; Brazil had a divergent trend of decreasing deforestation, >90% of which was attributable to a reduction in medium and large clearings. The emerging prominence of large-scale drivers of forest loss in many regions and countries suggests the growing need for policy interventions which target industrial-scale agricultural commodity producers. The experience in Brazil suggests that there are promising policy solutions to mitigate large-scale deforestation, but that these policy initiatives do not adequately address small-scale drivers. By providing up-to-date and spatially explicit information on the scale of deforestation, and the trends in these patterns over time, this study contributes valuable information for monitoring and designing effective interventions to address deforestation.

1. Introduction
Forest loss, which globally amounted to 230 000 kha from 2000–2012 (Hansen et al 2013), contributes to climate change, biodiversity loss, water quality degradation, and other negative impacts on ecosystem services (Foley et al 2005). In total, deforestation and forest degradation costs the global economy 2–4.5 trillion USD annually (Sukhdev 2008). Deforestation trends are projected to accelerate as demand for food, fiber and fuel from a rapidly growing population with shifting diet preferences puts increasing pressure on the world’s forests (Tilman et al 2011). The negative environmental impacts of forest loss will be most evident in the tropics, where the majority of future deforestation is anticipated (Laurance et al 2014, D’Annunzio et al 2015), and which hosts critical ecosystem services including biodiversity and carbon storage (Gibson et al 2011, Asner et al 2010).

Recent research has shown that agriculture is the dominant driver of forest conversion across the tropics, comprising > 80% of deforestation (Gibbs et al 2010, Hosonuma et al 2012). The proportion of this forest loss resulting from large commodity crop expansion, rather than small-scale farming, varies by country from 35%–68% (Hosonuma et al 2012).
However, the proportion of large versus small-scale drivers of forest loss is not static over time. Up-to-date and spatially explicit information on the scale of deforestation, and the trends in these patterns over time, is an essential step towards designing effective interventions to slow or reverse deforestation.

Many drivers of land cover change leave a traceable footprint in their wake, which can be observed from satellite imagery. The pattern of a particular driver will vary by locale, and be determined by a range of variables including production strategy, market integration, and access to technology and infrastructure (Graeub et al 2016). Nonetheless, the size of a forest clearing activity is often used as a proxy for characterizing small-scale activities versus large commercial and industrial-scale operations. For example, smallholder agriculture generally results in clearings smaller than <2 ha (World Bank 2003, Rapsomanikis 2015), and the FAO uses a threshold of 10 ha to define smallholder farms (FAO 2012b). On the other hand, large-scale commodity crop cultivation and commercial livestock ranching can result in forest clearings >1000 ha. Industrial oil palm plantations average >3000 ha in Indonesia (Austin et al 2013), while almost half of the land used for cattle grazing in Brazil is comprised of ranches >1000 ha (Carvalho 2006). In addition, the sale or lease of hundreds of thousands of hectares for export-driven agriculture has become more commonplace (Lambin and Meyfroidt 2011). Although agriculture is the predominant cause of deforestation in the tropics, there is also wide variability in forest clearing sizes due to other drivers of forest loss, such as mining, timber extraction, or urbanization. For example, the growth of individual artisanal mining areas may range from difficult to detect at 30 m resolution, to prominent and expanding at >1000 ha yr^{-1} (Swenson et al 2011). The ability to broadly distinguish small- versus large-scale activities is particularly important for characterizing deforestation in landscapes where more than one driver is operating (Malhi et al 2014), such as where smallholders collect fuel wood, cultivate crops and manage livestock on one farm, or in large-scale integrated crop-livestock systems (de Moraes et al 2014).

In this analysis we aim to improve understanding of trends in proximate drivers of pantropical deforestation by analyzing forest clearings of different sizes from 2000–2012. We use a global forest change product (Hansen et al 2013) to describe deforestation in terms of clearing sizes, and examine the proportion of different sized forest clearings over time by country, region and economic development group. While such an analysis has been conducted for Brazil (Rosa et al 2012, Assunção et al 2013, Godar et al 2014), a thorough analysis of the pantropics is lacking. This is particularly important, given that the declining rates of large-scale deforestation observed in Brazil may not be representative of the patterns of deforestation in other parts of the world. Here we provide a comprehensive pantropical comparison of the shifts in deforestation size classes over time. Our study complements previous studies of the drivers of deforestation across the tropics, which have been limited to reporting qualitative data that is not systematically collected, is available for only a single time-step, or is not spatially explicit (e.g. Rudel et al 2009, Hosonuma et al 2012). We refrain from identifying specific proximate drivers of change, for which detailed local data would be required on land use following clearing events (e.g. De Sy et al 2015).

2. Methods

We analyzed deforestation trends by clearing size with a global, 30 m resolution map of tree cover and forest loss between 2000 and 2012 (Hansen et al 2013, Version 1.1). Hansen et al (2013) define forest loss as the complete removal of tree cover at the mapping scale. We constrained our analysis to pixels with ≥ 50% tree canopy cover in 2000, as was done in the original study, and to the tropics using the FAO global ecological zoning framework criteria. FAO considers areas with all months frost free and over 18 °C in marine areas to be tropical (FAO 2012a). Countries spanning more than one ecological zone were considered tropical if the majority of their forest was in the tropical zone (Keenan et al 2015). We defined a clearing as a group of contiguous pixels (eight neighbor rule) where forest loss was observed in one year (figure 1). Although data on forest loss is now available through 2015, from 2013 onward this data was based on Landsat 8 OLI, for which full validation has not yet been completed (Hansen et al 2013). We therefore used the original dataset to ensure consistency across the time series.

We analyzed trends within four deforestation size classes and used two previous studies from Brazil as a guide for selecting these classes; Assunção et al (2013) used four classes with a minimum size <25 ha and a maximum size >500 ha, while Rosa et al (2012) used six classes with a minimum <50 ha and a maximum >1000 ha. We grouped clearings into four classes increasing on a log scale: <10 ha; 10–100 ha; 100–1000 ha; and >1000 ha. We selected the smallest size class threshold of <10 ha in order to distinguish household or smallholder activities across the tropics, while allowing for some flexibility to account for neighboring or grouped smallholder activities (Rapsomanikis 2015). Medium (10–100 ha) and large (100–1000 ha) generally represent commercial operations, although they may also indicate activity by wealthier individual landowners (Boucher et al 2011, Lawson et al 2014). The largest clearing size class >1000 ha differentiates industrial-scale
activities, including commercial agriculture, ranching, and plantations. We acknowledge that the thresholds distinguishing each size class may in some cases result in misclassifications. However, we assume that these misclassification errors have not become more or less likely over the study period 2000–2012, and therefore they are not likely to bias our result.

In order to determine whether the change in clearing sizes over time was significant, we ran linear regressions on (1) the proportion of small sized clearings <10 ha over time, (2) the rate of deforestation through time, and (3) the proportion of the two largest sized clearings (100–1000 ha and >1000 ha) over time. We repeated this procedure for each country, and for groups according to income level during the calendar year 2000 (World Bank 2015) and region (Keenan et al. 2015). The World Bank uses gross national income per capita to divide countries into four income groupings: low (e.g. Nicaragua, Madagascar), lower-middle (e.g. Ecuador, Thailand), upper-middle (e.g. Brazil, Malaysia), and high (e.g. Virgin Islands, Singapore) (World Bank 2015). We report those countries and regions with significant trends ($p < 0.1$).

Solitary pixels in datasets derived from satellite images are often associated with errors or noise and could lead to an overestimation of the amount of loss in small-scale forest clearings. To explore the effect of excluding small clearings from our analysis, we removed deforested clearings of 1- to 3-pixels (0.09–0.27 ha) from forest loss maps of Indonesia. The proportion of all clearings <10 ha across all years was 0.51; removing small clearings only slightly reduced the proportion of clearings detected in this size class (0.50 [1-pixel], 0.49 [1–2 pixels], and 0.48 [1–3 pixels]). We therefore retained all clearing sizes including solitary pixels in this analysis. Although our results are robust to the exclusion of these small clearings, it is possible that some of the observed small-scale changes are adjacent to or contained within large-scale deforestation that predated the time series, or that clustered smallholder activities occurring within one year appear as a single large-scale activity, concealing the true scale of change. We assume that these errors have not changed in frequency over the study period, and are therefore unlikely to bias our results.

Poor differentiation between native forests and plantations has been observed in the Hansen et al data set (Tropek et al. 2014). Therefore, some plantations established prior to the year 2000 may be undergoing harvesting cycles, which would be incorrectly attributed to deforestation in this and other studies. To test this possibility, we examined deforestation trends only within areas designated as primary forest for the year 2000 in Indonesia, which includes intact and degraded primary forest (e.g. mature forest blocks >5 ha) but excludes secondary forest and plantations (Margono et al. 2014). When we excluded pixels mapped as plantations and secondary forest, we still observed a significant trend with respect to the proportion of clearings sizes, consistent with our analysis of the complete Hansen forest loss dataset. Additional details are provided in the online supplementary data, available at stacks.iop.org/ERL/12/054009/mmedia. The Hansen dataset was not optimized for the detection of change in sparse or shorter forested types, such as savannahs, dry tropical forests or dense shrub ecosystems; these vegetation types are more challenging to characterize in general at this scale (González-Roglich and Swenson 2016), and estimates of loss in those areas could be less reliable (Hojas-Gascoen et al. 2015).
3. Results

Deforestation in the tropics increased by 53% between 2001 and 2012, from 6000 kha in 2001 to 9200 kha in 2012, according to the data from Hansen et al (2013). Over 80% of observed tropical deforestation occurred in just four countries: Brazil, Indonesia, Democratic Republic of Congo, and Malaysia. Deforestation increased significantly in 39 countries, led by Indonesia, the Democratic Republic of Congo, Malaysia, and Cambodia, where deforestation rates increased >10 000 ha yr\(^{-1}\) (figure 2(a)). On the other hand, deforestation rates decreased significantly in 11 countries led by Brazil, the only country which experienced a decrease of >1000 ha yr\(^{-1}\).

Across the tropics the proportion of forest loss comprised of small clearings (<10 ha) fluctuated between 53%–65%, decreasing from 2001–2004, increasing from 2004–2009, and subsequently declining again until 2012 (figure 3(a), online supplementary table S2). Over the same period, the proportion of deforestation in medium and large clearings (10–100 ha and 100–1000 ha) was roughly constant, and the proportion of very large clearings (>1000 ha) increased from 2% to 5%. However, when we excluded Brazil we found a clear decreasing trend in the proportion of deforestation in small clearings, from 78% to 61% (figure 3(b), table S2). Concurrently, the proportion of deforestation comprised of medium clearings increased from 13% to 20%, large clearings from 7% to 13%, and largest clearings from 2% to 5%.

Over the study period, 79% of deforestation in the tropics occurred in South America and Southeast Asia (figure 4(a)). In addition, the proportion of deforestation comprised of small clearings in these two regions was 42% and 67%, respectively, much lower than other regions where small clearings made up >80% of deforestation (figure 4(b)). Approximately 1400 kha of forest loss occurred in Southeast Asia in 2001, increasing to >3700 kha in 2012 (online supplementary table S1). This rapid increase in deforestation was driven principally by medium, large and very large clearings, which comprised 35% of deforestation in 2001 and 51% in 2012. However, the observed trend of increasing large clearings was not uniform among all of the countries in the region (figure 5). The expansion of large clearings drove the observed increase in deforestation in...
Cambodia, Indonesia and Malaysia, where the three largest clearing size classes contributed to 64%, 72%, and 76%, of the increase in average deforestation between the first and second half of the study period, respectively. On the other hand, in the Philippines and Thailand 92% and 90% of the increase in deforestation was due to the proliferation of small clearings.

We found that the regional downward trend in forest loss observed in South America was primarily due to reduced deforestation in Brazil, masking opposite trends in South American countries with smaller forested areas and lower rates of deforestation (figure 4). Average annual deforestation decreased in Brazil from approximately 3000 kha yr\(^{-1}\) to 2150 kha yr\(^{-1}\) between

![Figure 3](image-url) Figure 3. Changes in size distributions of forest clearings for all tropical countries (a) and excluding Brazil (b).

![Figure 4](image-url) Figure 4. Deforestation trends by region, (a) changes in area of forest loss, and (b) changes in the proportion (by area) of small clearings <10 ha. Thick lines and asterisks indicate significant trends over time (\(p\)-value <0.1). Dashed lines represent values for South America excluding Brazil.
the first and second halves of our study period, 55% of which was due to a reduction in large and very large clearings and an additional 39% of which was due to decreasing medium-sized clearings (figure 5). Outside of Brazil, approximately 700 kha of deforestation occurred in South America in 2001, increasing to >1200 kha in 2012 (table S1). The three largest clearing sizes also increased over this period, comprising 23% of deforestation in 2001 and 35% by the year 2012. The largest clearing size classes contributed to 81% of the observed increase in average deforestation between the first and second half of the study period in Paraguay, 68% of the observed increase in Uruguay, and 60% of the observed increase in Bolivia. However, the largest clearings contributed to less than half of the increase in deforestation observed in Peru, Venezuela, Colombia, and Ecuador (figure 5).

Examining deforestation trends across income groups over time, we found that the area of deforestation increased significantly while the proportion of small-scale clearings decreased significantly in low, lower middle, and upper middle income countries, excluding Brazil (figure 6). The trends in forest loss and clearing size were not significant for high income level countries (e.g. Singapore, the Virgin Islands). Notably the lowest income countries (e.g. Congo) had the highest proportion of small-scale clearings, followed by lower middle, then upper middle, and lastly high income countries. This fits expectations that as national economies grow, a larger proportion of clearings will be driven by large industrial-scale actors, and corresponds with findings from previous studies that average farm size increases as income increases (Lowder et al 2016, Adamopoulos and Restuccia 2014).

4. Discussion

4.1. Trends in size of clearings from 2001–2012

Our analysis demonstrates an overall increase in the proportion of deforestation comprised of medium,
large and very large clearings across the tropics 2001–2012. This trend is largely determined by patterns of forest loss in Southeast Asia and South America, excluding Brazil. Approximately 60% of the observed increase in deforestation in Southeast Asia and South America is due to increases in the three largest clearing sizes. Our results suggest the continuation of a trend identified by Rudel et al. (2009), who reported a transition from state-sponsored small-scale deforestation in the 1960s and 70s, to export-oriented industrial-scale deforestation in the 1980s and 90s, in the tropical regions of Southeast Asia and Latin America. Similarly, DeFries et al. (2010) found that small-scale clearings for household needs or local markets are increasingly overshadowed by forest loss associated with export-oriented agriculture. In addition, our results may reflect increasing international trade of hundreds of thousands of hectares of land in a single transaction, due to food security concerns (Rulli et al. 2013), and chiefly intended for export-driven agriculture (Lambin and Meyfroidt 2011). Our analysis suggests that these trends are continuing up to recent years, with the exception of Brazil.

However, we note that this increase in large clearings is not uniform across the tropics, or even among the Southeast Asian and South American regions. The factors which promote expansion of large-scale commercial agriculture, such as crop productivity, available land, governance structure, access to labor, markets and investment, land tenure and local land use policies vary widely among the countries in these regions (Deininger and Byerlee 2012). For example, Rudel (2013) proposed that small-scale agriculture continues to be the dominant form of deforestation in Africa. Regions with substantial tropical forest (e.g. Congo Basin) have experienced oil and mineral extraction booms, which may have encouraged urbanization and effectively spared forests (Rudel 2013). Furthermore, high transaction costs and investment risk resulted in reduced foreign financing (Brandt et al. 2016), less investment in infrastructure (Graesser et al. 2015, Mayaux et al. 2013), and fewer large agriculture projects (Rudel 2013).

We found that the countries experiencing significant increases in large-scale deforestation tend to be the lower to middle income countries, which is consistent with previous research (e.g. Tilman et al. 2011, Deininger and Byerlee 2012, Laurance et al. 2014). We observe that low income countries still have the highest proportion of small-scale clearings (60%), followed by middle income countries (50%), and upper middle income countries (40%). High income countries have the lowest proportion of small-scale clearings, and we do not observe a significant change in the size of clearings over time. These trends may be indicative of a forest transition, in which economic growth shifts deforestation patterns away from small-scale clearings, eventually resulting in an overall decline in rates of forest loss (Mather 1992).

4.2. Policy implications

The increasing dominance of large-scale drivers of forest loss in many countries, in particular Indonesia, Malaysia, Cambodia, Paraguay and Bolivia, suggests the need for policy interventions which target industrial commodity producers. Other researchers have highlighted the importance of addressing large-scale agriculture as a predominant driver of deforestation, due to concerns that it is encroaching on the last intact and biodiversity-rich forests in the tropics (Laurance et al. 2014), and due to insufficient evidence that even high-yielding intensive agriculture will spare land elsewhere for conservation (Lambin and Meyfroidt 2011).
Evidence from Brazil suggests that there are a range of promising policy solutions to address large-scale deforestation. Our results support previous findings from Rosa et al. (2012), Assunção et al. (2013), and Godar et al. (2014), who reported decreasing dominance of large industrial-scale drivers of forest loss in Brazil 2000–2010/2011. This trend is attributed to a combination of policy interventions including the Plan to Prevent and Combat Deforestation in the Amazon (PPCDA), improved monitoring and enforcement via the registration of rural properties (CAR) and the Real Time Deforestation Detection System (DETER), and voluntary sustainability initiatives in the soy and beef industries (Nepstad et al. 2014). Similar policy levers may be effective at reducing large-scale clearings in other regions and countries, including for example emerging voluntary sustainability commitments, which aim to eliminate deforestation from the supply chains of major globally-traded commodities such as palm oil (United Nations 2014).

Notably, however, these Brazilian policy initiatives have largely proven unsuccessful at addressing small-scale drivers of deforestation (Rosa et al. 2012; Godar et al. 2014), and may have resulted in a shift of deforestation to areas outside the scope of monitoring and enforcement, including areas outside the Amazon and possibly into neighboring countries (Richards et al. 2016). We estimate that <10% of the observed decrease in deforestation in Brazil 2001–2012 is due to a reduction in small-scale clearings. There are many regions where small clearings continue to dominate the deforestation profile, including most of Central America and Africa. Because small-scale conversion is often dispersed across multiple communities with diverse motivations and governing principles, the policy levers for addressing this type of conversion are more varied, and must be tailored to locally-specific contexts (Godar et al. 2014). Given its importance in these regions, it is clear that additional research is needed to support the development and enforcement of policies that address these diffuse and multi-stakeholder drivers of forest loss.

4.3. Priority next steps

The goal of our study was to track the changes in size classes of deforestation over time across the tropics. At this scale we do not identify specific proximate drivers of change for different regions. Characterizing drivers would require extensive local data and possibly the development of regional models linking deforestation characteristics (shape, orientation, or arrangement) with a reliable dataset on drivers of forest loss, such as accurate data from government statistics agencies, industry permit maps, or high resolution land cover data. Were such data available, comparing differences across administrative boundaries (e.g. registered logging or mining concessions) at regional scales could strengthen the analysis. Clearing sizes associated with specific drivers can vary substantially by country and region, being influenced by topography, stream and transportation network, land use policies and the activity itself.

Additional improvements to the present analysis include extending the study period backwards to capture the trends in deforestation size classes in the 80s and 90s, and to investigate whether observed trends have continued up to the present—this would be possible upon completion of a consistent forest loss dataset representing the entire Landsat thematic mapper time series. Such an analysis would be challenged by the sparse satellite acquisition record in the 1980s and 90s, though improvements to the historical archive are being made (Wulder et al. 2016). In addition, for the purpose of this study we assumed that any observed deforestation was clearing of natural forest and not harvesting of plantations established prior to the year 2000. We tested the impact of this assumption on our results in Indonesia, and found that the observed trend was not different from that observed using the full dataset. However, it would be valuable to test this assumption across the tropics with a detailed natural forest cover map. Finally, we assumed that all observed changes were the result of anthropogenic activities, and did not consider natural causes of land cover change such as drought or pests. Data on non-anthropogenic causes of forest loss are currently limited at the scale of our study, but could be incorporated as they become available.

5. Conclusion

Deforestation is increasing across the tropics, resulting in well-documented negative impacts on ecosystem functions and services. In order to effectively address this deforestation, interventions must be underpinned by improved understanding of the drivers of forest loss that they target. Each country and region will need to develop a suite of policy interventions that balance their unique portfolio of drivers. By providing up-to-date, consistent, and spatially explicit information on the scale of deforestation, and the trends in these patterns over time, this study contributes valuable information to inform the process of policy development.

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