Abstract

Protected areas in Guatemala provide habitat for diverse tropical ecosystems, contain ancient archeological sites, sequester carbon, and support economic activity through eco-tourism. However, many of the forests in these protected areas have been converted to other uses or degraded by human activity, and therefore are considered “paper parks”. In this study, we analyzed time series of satellite data to monitor deforestation, degradation, and natural disturbance throughout Guatemala from 2000 to 2017. A recently developed methodology, Continuous Degradation Detection (CODED), was used to detect forest disturbances of varying size and magnitude. Through sample-based statistical inference, we estimated that 854,137 ha ($\pm$ 83,133 ha) were deforested and 1,012,947 ha ($\pm$ 139,512 ha) of forest was disturbed but not converted during our study period. Forest disturbance in protected areas ranged from under 1% of a park’s area to over 95%. Our estimate of the extent of deforestation is similar to previous studies, however, degradation and natural disturbance affect a larger area. These results suggest that the total amount of forest disturbance can be significantly underestimated if degradation and natural disturbance are not taken into account. As a consequence, we found that the protected areas of Guatemala are more affected by disturbance than previously realized.

Introduction

In the 20th century, continued ecological destruction and land degradation which threaten biodiversity, traditional livelihoods, ecosystem services, and contributing to carbon emissions has been met with efforts to conserve tropical forests (“World Conservation Strategy”, 1980; Watson et al. 2014). Protected areas can facilitate forest conservation, but their success depends on effective measures to prohibit anthropogenic disturbance. Earth observation systems offer vital information for assessing the extent of human modification to protected areas, their success in limited damaging activities, and for prioritizing future conservation initiatives.

The largest increase in protected forestlands in the last two decades has been in Central America, with less than 3% of forests being protected prior to 1990, increasing to 15% in 2015 (Morales-Hidalgo et al. 2015). In parts of Central America these efforts have led to conservation and even forest transition, most notably in Costa Rica (Calvo-Alvarado et al. 2009). However, increased pressure from international commodity markets, lack of clear land tenure, ineffective enforcement against illegal land appropriation, organized crime, and population growth have led to large amounts of forest disturbance throughout the region (Sader et al. 1994; Tucker et al. 2005; Pirard 2008; Radachowsky et al. 2012; Weishampel et al. 2012). Consequently, many of the protected areas are considered “paper parks”, or areas legally designated as protected but contain forests at risk to human modification due to a lack of enforcement or oversight (Bonham et al. 2008).

The Mesoamerican Biological Corridor (MBC) provides a geographic link between the unique ecosystems of South, Central, and North America, and has therefore been a focus of conservation efforts in recent decades (DeClerck et al. 2010). In the heart of the MBC is Guatemala’s Maya Biosphere Reserve (MBR) which contains the largest expanse of continuous rainforest in Central America (Miller et al. 2001). The parks in the eastern portion of MBR also contain remnants of the ancient Mayan civilization, which are essential for the tourism industry of the country (Radachowsky et al. 2012). The MBR has also been globally recognized as an example of conservation through community forestry, with large...
parts of the reserve allocated as community concessions (Gretzinger 1998; Radachowsky et al. 2012). Despite these efforts, illegal logging remains prevalent. Between 2000 and 2013, Hodgdon and Ramos (2013) reported that deforestation in the Maya Reserve averaged 1.3% of the total forest cover per year. Additionally, the rate in the Core Zone, in which no logging is permitted, was 1%.

South of the MBR is the Sierra de las Minas Biosphere Reserve (SMBR), a mountainous region that has been identified as one of the most irreplaceable protected areas in the world (Saout et al. 2013). SMBR is named after its expansive mineral deposits, namely jade and marble. The mountain range contains both dry and humid cloud forests and is one of the most ecologically diverse areas in Central America. The reserve contains an estimated 885 species of vertebrates representing approximately 70% of the species in Guatemala (Nations et al. 1989). While a majority of the region was designated as a protected area in 1990, the rich mineral deposits and timber resources have made the area vulnerable to illegal logging and mining. From 1987 to 1995, the annual deforestation rate in the protected area was approximately 1860 ha per year (Lehnhoff and Nuñez 1998).

MBR and SMBR are two of over 350 protected areas in Guatemala, which in total comprise 32 percent of the country’s land area (Man 2011; CONAP, 2018). The land use policies of the protected areas vary, with some allowing tourism, low impact agriculture, and timber concessions (Radachowsky et al. 2012). Despite the extensive area of protected forests, environmental destruction in Guatemala remains high, with only Nicaragua having a higher rate of forest loss in Latin America and the Caribbean since 2000 (Aide et al. 2012). Using MODIS data, Leisher et al. (2013) found that land and forest degradation in Guatemala’s protected areas was occurring at twice the Latin American average from 2004 to 2009 and was taking place in over 40% of the nation’s protected areas.

Remote sensing analysis has allowed for effective monitoring of protected forests (Leisher et al. 2013) for deforestation or stand replacing disturbances (Hansen et al. 2013; Blankespoor et al. 2017). However, recent research suggests that such approaches can omit degradation and natural disturbance (D/ND), which result in a decrease in the ecological capacity of the forest without a land cover conversion (Baccini et al. 2017; Milodowski et al. 2017). Drivers of such events can be anthropogenic (forest degradation), or natural, with the key point being that the forest undergoes a disturbance without a land cover conversion, and hence have not been included in past analyses of change using remote sensing. Compared to intact forests, disturbed forests in Central America have been shown to be less ecologically productive (Holder 2006), lower in species diversity (Schulze et al. 2000; Renner and Walter 2006; Griscom and Ashton 2011), and lower in carbon storage (Castro et al. 2003). Despite the evidence on the detrimental impact of D/ND, it has not been included in most large area forest monitoring efforts due to methodological limitations (Herold et al. 2011; Goetz et al. 2014). However, recent advancements in data accessibility, storage, and processing have allowed for new approaches that take advantage of the full depth of the Landsat data archive (Kennedy et al. 2010; Verbesselt et al. 2010; Zhu and Woodcock 2014; Bullock et al. 2018). As a result, subtle processes such as D/ND can be mapped with greater accuracy and over larger areas than ever before possible.

In this study, we utilize time series analysis of satellite data to map forest disturbance in Guatemala from 2000 through 2017. We use a recently developed methodology, Continuous Degradation Detection (CODED) (Bullock et al. 2018), to differentiate deforestation from D/ND. The mapped dataset is used to assess the extent of disturbance in the country’s protected areas during our study period. The dataset is also used to select a collection of sample sites, which are assigned reference labels and used as the basis for unbiased estimates of area of disturbance.

Materials and Methods

Study area

The entire country of Guatemala was monitored for disturbance. Guatemala contains a mix of ecosystems including lowland humid, deciduous, and montane forests. The

| Table 1. Stratification used for deriving a stratified random sample |
|---------------------|---------------------------------|----------|
| Strata              | Description                     | Sample Allocation |
| Forest              | >30% Canopy cover of trees over 5 feet in height. | 0.43 400 |
| Non-Forest/Other    | Not meeting the definition of forest, can contain disturbances in other land covers and regrowth. | 0.37 300 |
| D/ND                | A disturbance in a forest that does not result in a change in land cover classification. | 0.08 150 |
| Deforestation       | A disturbance in a forest that results in a change in land cover classification. | 0.05 150 |
| Possible            | A one pixel buffer surrounding disturbances and pixels labeled as forest but high magnitude of change in the backup change detection algorithm. | 0.07 100 |

The sample was used to estimate map accuracy and unbiased area estimates for the country.
Pacific coast contains many volcanoes, all of which are protected. Coastal lowlands in Guatemala have largely been deforested before our study period, but the lowland humid forests in the North do not share similar land use histories. The boundaries of protected areas were provided by the Consejo Nacional de Áreas Protegidas (CONAP). The protected areas used in the analysis included national and municipal parks, wildlife and biosphere reserves, multiple use parks, volcanoes, and cultural sites. The study period was defined as 2000 through 2017.

### Monitoring forest disturbance

CODED was specifically developed to monitor for D/ND. Souza et al. (2005) demonstrated how spectral mixture analysis could be used to effectively discern locations that have undergone sub-pixel canopy damage due to fire or logging. Spectral unmixing was used to transform Landsat surface reflectance data into endmember proportions, from which the Normalized Difference Fraction Index (NDFI) is calculated. NDFI was shown to be more sensitive to disturbances than transforms based on spectral reflectance alone, such as the Normalized Difference Vegetation Index (NDVI) (Tucker 1979). CODED extends this approach into the time series domain by using NDFI as the basis for a regression-based algorithm for detection of structural breaks, or times when patterns no longer resemble the past. By fitting regression models to all available Landsat data, CODED is able to detect disturbance events that are visible from above the canopy for less than a year. CODED is open-source and is available on the Google Earth Engine (Gorelick et al. 2017)(see github.com/bullocke/coded).

In addition to finding changes in forest area, CODED uses the model regression coefficients as inputs to a

---

**Table 2.** Estimated areas and accuracies for the two change and two stable classes

| Class            | Estimated Area (%) | Estimated Area (Ha) | Standard Error (ha) | Margin of Error (%) | Map Bias (%) | Producer’s Accuracy (%) | User’s Accuracy (%) |
|------------------|--------------------|---------------------|---------------------|---------------------|--------------|------------------------|---------------------|
| Forest           | 43.19              | 4 885 638           | 207 345             | 8.32                | +3.36%       | 86.34                  | 86.40               |
| Non-Forest       | 40.31              | 4 560 348           | 178 905             | 7.69                | -9.62%       | 87.42                  | 94.67               |
| D/ND             | 8.95               | 1 012 947           | 139 512             | 26.99               | -27.24%      | 50.76                  | 85.23               |
| Deforestation    | 7.55               | 854 137             | 83 133              | 19.07               | +0.67%       | 84.41                  | 84.46               |

The margin of error is defined as the half width of the 95% confidence interval to the estimate. Map bias is defined as the percent difference between the estimated and map area. A negative bias means the area in map is underestimated. The Overall Accuracy of the map was 83.44%.

---

**Figure 1.** Mapped change detection results for the country (A), Lachuá Lake National Park (B), Sierra Caral National Protected Area (C), Lxíl Visis-Cabá Biosphere Reserve (D), and the Sierra de las Minas Biosphere Reserve (E). Sierra Caral was established in 2014 and therefore the disturbances reflect the time before and after the park designation.
Random Forests classifier to assign land cover labels for every location (pixel) and time period. Changes in a pixel classified as forest are labeled forest disturbance. If the land cover label after the event is forest the change is further labeled as D/ND, and if it is a different land cover it is labeled as deforestation.

**Sample-based area estimation**

Maps that are created using automated classification approaches inevitably contain errors and biases, and therefore it is recommended to avoid “pixel counting” when estimating areas, or extents, of land cover or change (Milne et al., 2003; McRoberts, 2011). A better approach is to use reference data from sample sites in a statistical estimator to obtain unbiased estimates of areas and their associated uncertainties (Olofsson et al., 2013b; Olofsson et al., 2014). These samples sites can be randomly selected across a study area, but in such a case the number of samples required to achieve adequate precision when estimating rare classes is often beyond feasibility (Stehman, 1999; Olofsson et al., 2014). Alternatively, maps can be used to stratify the study area from which a stratified random sample can be derived. Stratification based on maps has been shown to reduce the number of sample sites necessary to achieve the same precision of estimates compared to random sampling (Stehman, 2009, 2013; Olofsson et al., 2013, 2014).

We used the CODED results as the basis for a stratified random sample (Table 1). The stratification for sample selection was a preliminary version of the dataset due to time requirements for interpreting the sample. Interpretation was performed while the dataset was improved and the areas reported in this article are based on the final version of the dataset. Locations that underwent an initial forest disturbance followed by deforestation to another land cover were assigned to the Deforestation stratum.

Figure 2. Estimated forest area over time within protected areas. Non-Disturbed Forests indicates the area of forest that has not been converted or disturbed without deforestation since 2000, and Disturbed Forests represent the area of forests mapped as D/ND.

Figure 3. Percent forest cover in the Core, Buffer, and Multiple Use (MUZ) Zones (solid lines) and two Core Zone parks (dashed lines). Forest cover includes forests that were disturbed but remained forest. The Tigre National Park is adjacent to the Buffer Zone and has seen extensive deforestation, while the Mirador National Park is spatially isolated and has remained largely undisturbed.
stratum as previous research has found that errors of omission for change classes can have a large impact on the variance estimate (or a decrease in precision) due to the large area weight of the class that contains the omission error (Tyukavina et al. 2013; Bullock et al. 2018; Arévalo et al. 2019).

Three trained experts interpreted the samples using the AREA2 toolbox (see github.io/bullocke/area2). The interpreters did not know the stratum of the samples at the time of interpretation. All forest disturbance events within the study period were recorded as either deforestation or D/ND. Since stratification was performed on an earlier version of the dataset the typical stratified estimator could not be used (Stehman 2014). Therefore, accuracy and area estimation was performed for the country using indicator functions and a ratio estimator (Cochran 1977).

Results
National area estimates

The results of our analysis are summarized in Table 2. Deforestation and D/ND occurred throughout the study region and in almost every protected area (Fig. 1). An estimated 854 137 ha (±83 133 ha 95% CI) of forest was converted to another land cover and an additional 1 012 947 ha was affected by D/ND (±139 512 ha). The total area of forest disturbance represents 14.8% of the country and 27.6% of the forest area in 2000. Deforestation and D/ND represented 10.9% and 8.6% of the total area of the parks, respectively, and stable forest represented 60.9% (Fig. 2). For nine of the protected areas over 40% of the park area contained forest disturbance.

Figure 4. Three geographic regions used to discuss the likely factors driving disturbance in Guatemala. The regions are separated based on land use history and geography. Modern 20th and 21st century population expansion, low topography, and mature tropical forests define the northern moist lowland forests. The central montane and Atlantic forests have a relatively long history of land use that includes agriculture, logging, and mining, and with remaining forests on karstic or protected elevated terrain. The protected areas in the Pacific montane forests are primarily volcanoes or high elevation lakes.
during our study period. The protected areas with the most forest disturbance were the Aguateca Cultural Monu-
ment and the San Román Biological Reserve (95% and
90% converted or disturbed, respectively), and the least
disturbance occurred in Mirador-Río Azul and Tikal
National Parks (both > 99% stable forest). A complete list
of the area of forest disturbance for each protected area
analyzed can be found in the Data S1.

The parks within MBR contained 89% of the total
deforestation within protected areas. We estimated that
on average 1.0% of the forest area of MBR was deforested
each year between 2000 and 2017, similar to the estimated
1.2% deforested area per year reported in Hodgdon and
Ramos (2013). In addition to deforestation, however, we
found an additional 0.68% per year of D/ND. In total,
approximately 17% of the 2000 forest cover of MBR was
converted (274 600 ha) and an additional 11%
(134 300 ha) was affected by D/ND. The deforestation
rate was highest in the Buffer Zone (1.4% per year),
where deforestation is allowed under certain circum-
cstances. By 2017, however, only 17% of the Buffer Zone
remained undisturbed forest (Fig. 3). In sharp contrast to
MBR, the rate of D/ND in SMBR (1 333 ha per year) was
over twice the deforestation rate (499 ha per year).

The overall accuracy of the map was 83.44%, and the
User’s Accuracy for each class was above 84% (Table 2).
The Producer’s Accuracies for Forest, Non Forest, and
Forest Deforestation were above 84%, and for D/ND it
was 50.75%. The margin of error for the area estimates,
defined as the ratio of the half width of the 95% confi-
dence intervals to the estimate, for Deforestation and D/
ND were 19% and 27% respectively.

Discussion
Anthropogenic and natural disturbance affected every
protected area in Guatemala from 2000 to 2017, however,
the parks varied in the intensity, extent, and types of dis-
turbance contained within their boundaries. The distur-
bance patterns reflect regional and local differences in
historical land use and resource demand, forest types,
and accessibility. While detailed attribution of disturbance dri-
vers was beyond the scope of this research, it is worth
discussing the demographic and environmental factors
that are likely driving disturbance. To do so, the country
was divided into three regions that share similar ecosys-
tems and land use practices: The northern lowland moist
forests, the central montane forests and Atlantic forests,
and the Pacific montane forests (Fig. 4).

Northern lowland moist forests
Deforestation in the northern state of Petén has been pre-
viously attributed to intense population growth and sub-
sequent agricultural intensification that occurred during
the second half of the 20th century (Shriar 2001). While
the entire country has a similar population density to Petén, the recent growth is unique to the north. The high demand for forest resources, in addition to a lack of enforcement of rules defining forest protections, have contributed to large areas of forest within MBR being deforested for alternative land uses. At the current deforestation rate, the MBR Buffer Zone will be entirely non-forest by 2030. There were also indications during our study period of pressure to deforest land in the Core Zone, as can be seen in the Laguna del Tigre National Park (LT; Figure 5).

Accessibility to population centers and roads likely contributed to the high frequency of disturbance in Petén. For example, the proximity to the Buffer Zone and the Mexico border likely influenced the high rate of activity in LT, as the park has been heavily used as a corridor for drug, gun, and artifact smuggling (Bird 2012). Conversely, the Mirador National Park, which is sparsely populated and only accessible by roads during the dry season, maintained near-100% forest cover for the entire study period (Fig. 6).

The parks with easy accessibility but low disturbance correspond to the parks containing important cultural sites and, consequently, offer economic opportunities through tourism. These parks include the archeological sites in the southern Core Zone and El Rosario National Park in southern Petén (Fig. 4). These results suggest that the disturbance in Petén is influenced by population growth, contraband, lack of enforcement of forest laws in parks without frequent tourism, and accessibility.

Central mountainous region

Protected forests in the central mountainous region were primarily affected by D/ND rather than deforestation. This region contains the two Departments with the highest rates of D/ND, Izabel and Alta Verapaz (Fig. 7). This forests in this region are frequently affected by legal and illegal logging and mining (Lehnhoff and Núñez 1998). Logging in a forest without land cover deforestation is, according to our definition, considered D/ND. The same is true for exploratory mines that do not develop into full mining operations. The remaining forestland in this region is largely karst, which is characterized by uneven terrain, underground drainage systems, and soft soils, making large parts of the landscape challenging for agricultural use. The karst and mountainous terrain, in addition to the large amounts of land deforested before our

Figure 6. Landsat images (TM/ETM+ 5-4-3 stretch) before and after the study period in El Rosario National Park and San Román Biological Reserve. Both reserves are located in the Petén region of northern Guatemala. However, little disturbance occurred in El Rosario, while San Román was almost entirely cleared. D/ND is abbreviated as DRF in the legends.

© 2019 The Authors. Remote Sensing in Ecology and Conservation published by John Wiley & Sons Ltd on behalf of Zoological Society of London.
study period, limit the possible geographic extent of deforestation in the region. Therefore D/ND, likely driven by small-scale logging and mining, is more prevalent than deforestation in the region.

A park that clearly demonstrates this pattern is the SMBR. Figure 8 shows an area that has been significantly impacted by logging in SMBR. While the logging did not result in deforestation, it did create a highly disturbed landscape. Therefore, the disturbance is labeled as D/ND. As discussed in Saout et al. (2013), SMBR contains a high number of endemic species and is therefore one of the most irreplaceable protected areas in the world. Our results suggest that the SMBR, in contrast with the lowland parks in Petén, is more threatened by D/ND than deforestation.

**Pacific montane forests**

The remaining protected forests in the Pacific montane region are primarily on volcanoes, where deforestation to pastureland or agriculture is challenging. Disturbance in the protected volcano parks is primarily due to erosion or fire, both of which can be natural or influenced by human activity. This region, including the frequented alpine Lake Atitlán, were also heavily damaged by Hurricane Stan in 2005 (Hernandez et al. 2011). Overall, D/ND and deforestation affected 9.6% and 3.6% of the forest area in the protected volcanoes, respectively. Based on this information, we hypothesize that disturbance in the Pacific Highlands is driven primarily incidental damage from human or natural activity.

**National estimates**

Our estimate of deforestation (854 137 ± 83 133 ha) is similar to that of the United Nations Food and Agriculture Organization (FAO), which reported that anthropogenic drivers led to 846 000 ha of deforestation from 2000 to 2015 (MacDicken et al. 2016). Although the time intervals differ, the 2016–2017 period represented only 2.5% of our total estimated area of deforestation. The FAO report, however, does not include the area of D/ND, which represents over 50% of our estimate for total area of disturbance. In other words, our total disturbance area is over double the area reported by FAO. The only two Departments where there were higher proportions of deforestation than D/ND were Petén and Retalhuleu.
These results support the hypothesis that the total area of forest disturbance will often be significantly underestimated if D/ND is not included (Milodowski et al. 2017).

Study limitations

This study analyzed trends in deforestation and D/ND over time within the boundaries of protected areas. However, it is possible for the protected areas to have the adverse affect of increasing disturbance outside the park boundary, also known as disturbance “leakage” (Andam et al. 2008). In such occurrence, the protected area would not be succeeding in the ultimate goal of reducing disturbance. We did not attempt to analyze “leakage” of disturbance into nearby non-protected forests, but the dataset created for this study would be suitable for doing so. Such research should consider the relative ecological importance of the protected areas when compared to the non-protected forests nearby. Unlike other tropical regions, most of the mature natural forest in Guatemala is protected. We therefore believe that, in ecologically vital forests such as those in the MBC or SMBR, disturbance “leakage” would not be an appropriate measure of the effectiveness of the protected areas.

Remote sensing of forest disturbance

The low Producer’s Accuracy of the D/ND class indicates that many disturbance events were omitted in the map. CODED has been shown to be more vulnerable to errors of omission than commission for detecting disturbances, resulting in map areas that underestimate the unbiased areas obtained from the sample (Bullock et al. 2018). CODED was modeled after the Continuous Change Detection and Classification (CCDC) algorithm for land cover monitoring. Both algorithms monitor for change using a similar regression-based test statistic that is computed by comparing an observation’s residuals to the model root-mean-squared error during a training period. Therefore both algorithms are prone to omission errors in situations in which a change process does not greatly exceed the normal variability in the data. By requiring multiple consecutive observations to exceed a statistical boundary, however, the change detection approach used in CODED and CCDC is robust to false detection of change. In fact, when comparing multiple forest monitoring algorithms Cohen et al. (2017) found CCDC to be the least prone to errors of commission but susceptible to omission errors. Variability can be high in Landsat data in tropical environments due to unfiltered clouds, cloud
Forest Disturbance in Guatemala’s Protected Areas  E. L. Bullock et al.

shadows, or atmospheric constituents. Furthermore, D/ND does not always result in a complete clearing of the canopy, and therefore the spectral change may be small compared to the natural variability. These factors likely influence the high omission rate of CODED in this study. The unbiased statistical estimator accounts for these errors when calculating countrywide areas of disturbance. However it was not possible to account for this bias when calculating areas within individual parks, as it would require sufficient reference samples within the boundaries of each protected area.

While CODED omitted a large amount of disturbances, the Possible Forest Disturbance stratum contained 18 of the errors of omission for D/ND. The small area weight of the Possible Forest Disturbance stratum relative to the Forest stratum had the effect of reducing the impact of the errors of omission on the variance estimate of the change classes (Table 1). The reasonably high accuracies of the map, in addition to the choice in stratification, allowed for the estimation of change area with reasonably small margins of error (19% and 27% for deforestation and D/ND respectively).

Conclusions

Protected areas, by definition, are meant to preserve the ecological and cultural integrity of a park or region (Dudley 2008). Our results show that the protected forests in Guatemala are more vulnerable to disturbance than previously reported. While our estimates of deforestation are similar to estimates of deforestation reported by the FAO and in previous studies, we found that deforestation accounts for less than half the total area of forest loss. However, the extent and types of disturbance varied by region. In locations with a long history of land use the protected forests are often on terrain unsuitable for alternative land uses, and thus disturbance is driven by small-scale disturbance in remaining forests. This disturbance can be disruptive to fragile natural ecosystems such as SMBR, but may be less damaging to volcano parks that were not designated primarily to preserve ecological integrity. Contrarily, protected areas in MBR are part of an essential natural corridor that has a relatively short history of land use, yet some are primarily “paper parks” and thus highly threatened by deforestation.

Furthermore, our research demonstrates how the historical Landsat archive is an irreplaceable resource for monitoring surface conditions. Together with cloud computing systems such as the Google Earth Engine, advanced change detection algorithms, and sample-based statistical inference, subtle processes such as D/ND can be monitored over large areas. These powerful new tools can be used to provide greater insight into the effectiveness of protected areas. Future assessments of the effectiveness of protected areas should include both D/ND and deforestation, and management policies should reflect the specific threats that are relevant to the region.

Acknowledgments

This research was funded by NASA through the NASA Earth Science Fellowship (16-EARTH16F-295), the USGS Landsat Science Team Program for Better Use of the Landsat Temporal Domain: Monitoring Land Cover Type, Condition and Change (grant number G12PC00070), and the Inter-American Development Bank (IDB). We would like to thank all our collaborators at the IDB and Consejo Nacional de Áreas Protegidas (CONAP), Wildlife Conservation Society (WCS), Universidad del Valle, and the Registro de Información Catastral (RIC). Specially, we thank Victor Ramos (WCS), Diego Incer, and Edwin Castellanos (Universidad del Valle) for the detailed feedback on our disturbance dataset. Additionally, we would like to thank Xianfei Shen and Yihao Liu for helping with sample interpretation. Finally, we thank the USGS and Google Earth Engine for the data and software used for our analysis.

References

Aide, T., M. Clark, H. Grau, D. López-Carr, M. Levy, D. Redo, et al. 2012. Deforestation and reforestation of Latin America and the Caribbean (2001–2010). Biotropica 45, 262–271.

Andam, K. S., P. J. Ferraro, A. Pfaff, G. A. Sanchez-Azofeifa, and J. A. Robalino. 2008. Measuring the effectiveness of protected area networks in reducing deforestation. Proc. Natl Acad. Sci. 105, 16089–16094.

Arrávalo, P., P. Olofsson, and C. E. Woodcock. 2019. Continuous monitoring of land change activities and post-disturbance dynamics from Landsat time series: a test methodology for REDD+ reporting. Remote Sens. Environ. https://doi.org/10.1016/j.rse.2019.01.013, in press.

Baccini, A., W. Walker, L. Carvalho, M. Farina, D. Sulla-Menashe, and R. A. Houghton. 2017. Tropical forests are a net carbon source based on aboveground measurements of gain and loss. Science 358, 230–234.

Bird, B. A. 2012. Drugs and Business : Central America Faces Another Round of Violence. Pp. 35–36

Blankespoor, B., S. Dasgupta, and D. Wheeler. 2017. Protected areas and deforestation: new results from high-resolution panel data. Natural Resources Forum 41, 55–68.

Bonham, C. A., E. Sacayon, and E. Tzi. 2008. Protecting imperiled “paper parks”: potential lessons from the Sierra Chinajá, Guatemala. Biodivers. Conserv. 17, 1581–1593.

Bullock, E. L., C. E. Woodcock, and P. Olofsson. 2018. Monitoring tropical forest degradation using spectral...
unmixing and Landsat time series analysis. Remote Sens. Environ., https://doi.org/10.1016/j.rse.2018.11.011.

Calvo-Alvarado, J., B. McLennan, A. Sanchez-Azofeifa, and T. Garvin. 2009. Deforestation and forest restoration in Guanacaste, Costa Rica: putting conservation policies in context. For. Ecol. Manage. 258, 931–940.

Castro, K. L., G. A. Sanchez-Azofeifa, and B. Rivard. 2003. Monitoring secondary tropical forests using space-borne data: implications for Central America. Int. J. Remote Sens. 24, 1853–1894.

Cochran, W.G. 1977. Sampling Techniques. John Wiley and Sons, New York.

Cohen, W., S. Healey, Z. Yang, S. Stehman, C. Brewer, E. Brooks, et al. 2017. How similar are forest disturbance maps derived from different landsat time series algorithms? Forests 8, 98.

CONAP. 2018. Listado de Areas Protegidas [WWW Document]. Sistema Guatemalteco de Areas Protegidas. DeClerck, F. A. J., R. Chazdon, K. D. Holl, J. C. Mild, B. Finegan, A. Martinez-Salinas, et al. 2010. Biodiversity conservation in human-modified landscapes of Mesoamerica: past, present and future. Biol. Cons. 143, 2301–2313.

Dudley, N. 2008. Guidelines for applying protected area management categories. Iucn.

Fund, I.U. for C. of N. and W.W., 1980. World conservation strategy: living resource conservation for sustainable development. IUCN, Gland, Switzerland.

Goetz, S. J., M. Hansen, R. A. Houghton, W. Walker, N. Laporte, J. Busch, et al. 2014. Measurement and Monitoring for REDD+: The Needs, Current Technological Capabilities, and Future Potential. Climate and Forest Paper Series 49.

Gorelick, N., M. Hancher, M. Dixon, S. Ilyushchenko, D. Thau, and R. Moore. 2017. Google Earth engine: planetary-scale geospatial analysis for everyone. Remote Sens. Environ. 202, 18–27.

Gretzinger, S. P. 1998. Community forest concessions: an economic alternative for the Maya Biosphere Reserve in the Petén, Guatemala. Timber, Tourists, and Temples 111–124.

Griscom, H. P., and M. S. Ashton. 2011. Restoration of dry tropical forests in Central America: a review of pattern and process. For. Ecol. Manage. 261, 1564–1579.

Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, et al. 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853.

Hernandez, B., A. Flores, B. Garcia, and A. Clemente. 2011. Satellite Monitoring of Lake Atitlan in Guatemala. Building Knowledge Bridges for a Sustainable Water Future 234.

Herold, M., R. M. Román-Cuesta, D. Mollicone, Y. Hirata, P. Van Laake, G. P. Asner, et al. 2011. Options for monitoring and estimating historical carbon emissions from forest degradation in the context of REDD+. Carbon Balance Manage. 6, 13.

Hodgdon, B. D., and V. H. Ramos. 2013. Deforestation trends in the Maya biosphere reserve. Guatemala.

Holder, C. D. 2006. The hydrological significance of cloud forests in the Sierra de las Minas Biosphere Reserve, Guatemala. Geoforum 37, 82–93.

Kennedy, R. E., Z. Yang, and W. B. Cohen. 2010. Detecting trends in forest disturbance and recovery using yearly Landsat time series: I. LandTrendr - Temporal segmentation algorithms. Remote Sens. Environ. 114, 2897–2910.

Lehnhoff, A., and O. Nuñez. 1998. Guatemala: sierra de las Minas Biosphere Reserve. Parks in Peril, People, Politics and Protected Areas.

Leisher, C., J. Touval, S. M. Hess, T. M. Boucher, and L. Reymondin. 2013. Land and forest degradation inside protected areas in Latin America. Diversity 5, 779–795.

MacDicken, K., Ó. Jonsson, L. Piña, S. Maulo, V. Contessa, Y. Adikari, et al. 2016. Evaluación de los recursos forestales mundiales 2015: cómo están cambiando los bosques del mundo?

Man, U. 2011. World Database on Protected Areas WDPA.

McRoberts, R. E. 2011. Satellite image-based maps: scientific inference of pretty pictures? Remote Sens. Environ. 115, 715–724. https://doi.org/10.1016/j.rse.2010.10.013.

Miller, K., E. Chang, and N. Johnson. 2001. Defining common ground for the Mesoamerican Biological Corridor. World Resources Institute, Washington DC, USA.

Milne, R., B. P. Jallow, D. Arrouays, P. Beets, P. Drichi, I. B. Harun, et al. 2003. Chapter 2: Basis for Consistent Representation of Land Areas. Good Practice Guidance for Land Use, Land-Use Change and Forestry IPCC National Greenhouse Gas Inventories Programme Intergovernmental Panel on Climate Change. Technical Support Unit.

Milodowski, D. T., E. T. A. Mitchard, and M. Williams. 2017. Forest loss maps from regional satellite monitoring systematically underestimate deforestation in two rapidly changing parts of the Amazon. Environ. Res. Lett. 12, 094003.

Morales-Hidalgo, D., S. N. Oswalt, and E. Somanathan. 2015. Status and trends in global primary forest, protected areas, and areas designated for conservation of biodiversity from the Global Forest Resources Assessment 2015. For. Ecol. Manage. 352, 68–77.

Nations, J.D., B. Houseal, I. Ponciano, S. Billy, J. Godoy, F. Castro, et al. 1989. Biodiversidad en Guatemala: evaluación de la diversidad biológica y los bosques tropicales. El Instituto Internacional para el Medio Ambiente y el Desarrollo, Washington DC.

Olofsson, P., G. M. Foody, S. V. Stehman, and C. E. Woodcock. 2013. Making better use of accuracy data in land change studies: estimating accuracy and area and quantifying uncertainty using stratified estimation. Remote Sens. Environ. 129, 122–131.

Olofsson, P., G. M. Foody, M. Herold, S. V. Stehman, C. E. Woodcock, and M. A. Wulder. 2014. Good practices for
estimating area and assessing accuracy of land change. Remote Sens. Environ. 148, 42–57.

Pirard, R. 2008. Estimating opportunity costs of Avoided Deforestation (REDD): application of a flexible stepwise approach to the Indonesian pulp sector. Int. Forest Rev. 10, 11.

Radachowsky, J., V. H. Ramos, R. McNab, E. H. Baur, and N. Kazakov. 2012. Forest concessions in the Maya biosphere reserve, Guatemala: a decade later. For. Ecol. Manage. 268, 18–28.

Renner, S., and M. Waltert. 2006. Forest Comparison of Bird Communities in Primary vs Young Secondary Tropical Montane Cloud Forest in Guatemala and Management. https://doi.org/10.1007/978-1-4020-5208-8.

Sader, S., T. Sever, J. Smoot, and M. Richards. 1994. Forest change estimates for the Northern Peten Region of Guatemala: 1986–1990. Human Ecology 22, 317–332.

Saout, S. Le, M. Hoffmann, Y. Shi, A. Hughes, C. Bernard, T. M. Brooks, et al. 2013. Protected areas and effective biodiversity conservation. Nature 342, 803–806.

Schulze, M. D., N. E. Seavy, and D. F. Whitacre. 2000. A Comparison of the Phyllostomid Bat Assemblages in Undisturbed Neotropical Forest and in Forest Fragments of a Slash-and-Burn Farming Mosaic in Peten, Guatemala. Biotropica 32, 174–184.

Shriar, A. J. 2001. The Dynamics of Agricultural Intensification and Resource Conservation in The Dynamics of Agricultural Intensification and Resource Conservation in the Buffer Zone of the Maya Biosphere Reserve, Peten, Guatemala. Hum. Ecol. 29, 27–48.

Souza, C. M. Jr, D. A. Roberts, and M. A. Cochrane. 2005. Combining spectral and spatial information to map canopy damage from selective logging and forest fires. Remote Sens. Environ. 98, 329–343. https://doi.org/10.1016/j.rse.2005.07.013.

Stehman, S. V. 1999. Basic probability sampling designs for thematic map accuracy assessment. Int. J. Remote Sens. 20, 2423–2441.

Stehman, S. V. 2009. Sampling designs for accuracy assessment of land cover. Int. J. Remote Sens. 30, 5243–5272.

Stehman, S. V. 2013. Estimating area from an accuracy assessment error matrix. Remote Sens. Environ. 132, 202–211.

Stehman, S. V. 2014. Estimating area and map accuracy for stratified random sampling when the strata are different from the map classes. Int. J. Remote Sens. 35, 4923–4939.

Tucker, C. J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8, 127–150.

Tucker, C. M., D. K. Munroe, H. Nagendra, and J. Southworth. 2005. Comparative spatial analyses of forest conservation and change in Honduras and Guatemala. Conserv. Soc. 3, 174–200.

Tyukavina, A., S. V. Stehman, P. V. Potapov, S. A. Turubanova, A. Baccini, S. J. Goetz, et al. 2013. National-scale estimation of gross forest aboveground carbon loss: a case study of the Democratic Republic of the Congo. Environ. Res. Lett. 8.

Verbesselt, J., R. Hyndman, G. Newnham, and D. Culvenor. 2010. Detecting trend and seasonal changes in satellite image time series. Remote Sens. Environ. 114, 106–115.

Watson, J. E. M., N. Dudley, D. B. Segan, and M. Hockings. 2014. The performance and potential of protected areas. Nature 515, 67–73.

Weishampel, J. F., J. N. Hightower, A. F. Chase, and D. Z. Chase. 2012. Use of airborne LiDAR to delineate canopy degradation and encroachment along the Guatemala-Belize border. Trop. Conserv. Sci. 5, 12–24.

Zhu, Z., and C. E. Woodcock. 2014. Continuous change detection and classification of land cover using all available Landsat data. Remote Sens. Environ. 144, 152–171.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Data S1. Supplemental Materials