Guyana Forestry Commission

Contract No: GFC 31/03/2015

May 2016

Forest Degradation Around Mined Areas: Methods and Data Analyses for Estimating Emission Factors: Version 2

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Contents

Acknowledgements

The field work was conducted primarily by staff from Winrock (WI) and Guyana Forestry Commission (GFC), with assistance from staff of Durham University (DU), and Indufor Asia Pacific (IAP). GFC, DU, and IAP were also very helpful in locating the potential sampling sites and data collection methods. Special thanks to Hans Sukhdeo (GFC), Towana Smarrt (GFC), Rosa Rivas Palma (IAP), Lara Murray (WI), and K. Goslee (WI and was a co-author the first version or report).

Cite report as:

Brown, S. and A. R. J. Mahmood. 2016. Forest degradation around mined areas: Methods and data analyses for estimating emission factors: Version 2. Submitted by Winrock International to Guyana Forestry Commission.

EXECUTIVE SUMMARY

The degradation of forests in developing countries is perceived to be important for global greenhouse gas emissions. One land use that results in forest degradation in Guyana, as well as its neighboring countries, is activity associated with gold mining. Mining itself, along with infrastructure associated with gold mining, such as roads and mining camps, results in deforestation. However, the forests adjacent to mines are often disturbed by the mining activity so that the carbon stocks are reduced even though forest cover remains. Such impact occurs for a number of reasons, such as when trees are removed to provide wood for building mining camps or when mine tailings lead to tree mortality. The purpose of this paper is to: 1) describe and test two methods for estimating the area of forest degradation (i.e. activity data [AD]) and the corresponding emission factors (EF) from mining, 2), provide estimates of the total emissions from forest degradation adjacent to mining areas, 3) compare the efficacy of estimating emissions by these two methods, 4) compare the emissions from forest degradation with emissions from deforestation, and 5) recommend appropriate methods for moving forward in Guyana and other countries.

Estimating the AD was based on a method developed to identify the extent of degradation resulting from mining activities—this area was found to be a 100 m wide buffer around identified deforestation areas due to mining (from the remote sensing work). Estimates of EFs were based on collecting data on tree mortality due to mining activities in preselected transects. In the first method, transects across the whole width of the 100 m buffer were located around polygons mapped as deforestation from mining—termed as non-mapped transects. In the second method, 100 m-long transects were located within areas that were identified and mapped as being degraded using 5 m resolution RapidEye multispectral imagery and GeoVantage aerial imagery--, termed as mapped transects.

In each transect for both methods, the dbh ≥ 10 cm (or basal diameter) and the species of those trees whose damage was, based on expert opinion of the field team, due to human impact from the mining activities—e.g. cutting, snapped, broken, root damage (washed out roots or buried roots), impact by toxic mining waste, trail construction, or flooding--was recorded. Only trees whose mortality is caused by human impacts from mining activities were recorded in this phase.

In addition to recording mining damaged trees, the dbh and species of all live and standing dead trees (mortality not caused by mining activity) along the transect were also recorded. Such data were collected in a total of 62 transects, with 41 in non-mapped areas (i.e. within the 100 m buffer around deforestation polygons) and 21 in mapped areas (i.e. within the identified degraded polygons). All tree measurements were used to estimate their biomass (using the same allometric equation used in all forest carbon work for GFC and carbon content per ha, and then subject to various statistical analyses.

About 60% of the non-mapped transects lost 10 Mg C.ha^{-1} or less in trees due to mining damage and almost 40% of these transects had no damage. In contrast, 43% of the mapped transect lost <10 Mg C.ha^{-1} due to mining but only 24% of the transects exhibited no loss in carbon due to mining damage. Mining damaged and other damaged trees were non-normally distributed and instead were skewed with high outliers, thus the Wilcoxon Rank-sum test (for analyses with non-normal distributions) was used for statistical analyses. The median is considered a better measure of the central tendency of the data set in these cases. The Wilcoxon test showed that difference in the underlying distributions of the carbon loss associate with mining damage by year were not significant.

The median carbon lost per transect type and year due to mining damage ranged from 0.9 to 19.5 Mg C.ha^{-1}.The median loss in carbon stock from mining damage, with 95% confidence interval in parentheses, across all years

for the non-mapped transects was 2.2 Mg $C.ha^{-1}$ (0.0 - 10.2 Mg $C.ha^{-1}$); and for the mapped transects it was 13.0 Mg $C.ha^{-1}$ (1.4-21.1 Mg $C.ha^{-1}$).

The carbon loss from degradation associated with mining based on the median EF represents 1.0% and 6.5% of the mean total aboveground carbon stocks for non-mapped and mapped transects, respectively. As a percent of emissions from all causes of deforestation plus logging, emissions from degradation around mining sites was about 1.8% and 0.8% for non-mapped and mapped transects, respectively.

In conclusion, both approaches clearly indicate that emissions from forest degradation around mining sites is insignificant. The time cost to estimate the area of the 100 m buffer around the deforested areas from mining is significantly lower than manually mapping the degraded areas, thus it is recommended that if mining degradation is to be reported the non-mapped method should be used. However, it is hard to make a case for the continuation of this monitoring process. The carbon impact of forest degradation due to mining presented here represents only the gross emissions and does not take into account how persistent the degradation might be or any regrowth and forest recovery—inclusion of any regrowth would reduce the emissions even further to practically zero.

INTRODUCTION

International emission reduction programs (especially REDD+) have focused mostly on deforestation because robust and well-tested methods and data are available for monitoring such changes across forested landscapes and there is a general consensus on its definition. In contrast, although degradation of forests in developing countries is perceived to be important for global greenhouse gas emissions (GHG), consideration rarely goes beyond this perception mostly due to the lack of data and methods for monitoring this activity. Moreover, there is no clear consensus on the definition of forest degradation and it contains phrases such as long-term loss persisting for X years or Y% of forest carbon stocks with no specification as to the value of these thresholds (GOFC-GOLD 2011). The World Bank (2013) under its Carbon Fund requires emissions from forest degradation to be accounted where 'significant' – defined as more than 10% of 'forest-related emissions'. Yet it is unclear what activities cause significant forest degradation, how to show significance meaningfully, or how to account for emissions cost-effectively when significant.

Many activities cause forest degradation but not all of them can be monitored well with high certainty, and not all of them need to be monitored using remote sensing data, though being able to use such data would give more confidence to reported emissions from degradation (GOFC-GOLD 2011). To develop a monitoring system for forest degradation, it is first necessary that the causes of degradation be identified and the likely impact on the carbon stocks be assessed. Examples of activities that cause forest degradation include the areas around deforested sites caused by surface mining for e.g. gold and other valuable minerals, legal and illegal selective logging, human-set fires that escape into the forest, over-exploitation of forest by fuelwood collection, and animal grazing that prevents regeneration. Mining with associated infrastructure, such as roads and mining camps, results in observable deforestation, but the adjacent forests are impacted by the mining activity due to a number of reasons, such as when trees are removed to provide wood for building mining camps, when mine tailings or permanent flooding lead to tree mortality, or when areas are subjected to pre-mining exploration. The area of forest undergoing selective logging with the presence of gaps, roads, skidding trails etc. is observable in satellite imagery. Although the presence of anthropogenic fires (practically all are anthropogenic as there is practically no dry electrical storms in tropical humid areas) in the forest landscape is observable, their areal extent is more difficult to monitor with the current suite of satellites.

Two basic elements are needed to estimate GHG emissions associated with forest degradation: activity data and emission factors. "Activity data" (AD) refer to the quantity of an activity that results in emissions, such as area in hectares of land degraded. "Emission factors" (EF) are the estimated amount of emissions of GHGs per unit of activity, such as Mg of carbon emitted per hectare degraded. EF are combined with AD to estimate total emissions from the activity. Because AD and EF are combined to estimate emissions, their units must agree. In addition, the stratification system used to develop the AD and EF must correspond.

A method for estimating gross emissions from forest degradation due to selective logging in tropical forests has been developed by Pearson et al. (2014) using the IPCC gain-loss approach (IPCC, 2003). This approach focuses on direct change in carbon stocks and therefore requires measurement of tree mortality and damage rather than an estimation of the difference in carbon stocks before and after a degrading event. This method has been found to be more appropriate for estimating the impact of degrading activities, especially when carbon stocks are variable across the forest and the carbon loss is relatively small. In such situations, the gain-loss approach requires fewer measurements to reach a reasonable level of certainty than would be required by measuring carbon stocks before and after damage.

We propose that this approach can be used to estimate the emissions from forest degrading activities related to gold mining by measuring damaged trees in the vicinity of mined areas. Because the intent is to focus strictly on carbon loss that result from human activity, it is critical that measurements are focused on trees (or stumps) whose mortality is caused by human impact, such as harvesting to build a mining camp or a trail or mortality as a result of flooding or mine tailings. Any tree damage that is a result of natural causes such as insect or disease should not be measured unless it is determined by expert opinion that there is a direct link to human activities. In this approach, gains by regrowth and recovery are not included at this time—the focus is on gross emissions.

The purpose of the study was to develop and test methods for estimating gross carbon emissions caused by degradation due to gold mining in Guyana, where gold mining is the main cause of deforestation. Two methods were developed to provide estimates of the AD and EF and both were implemented to determine which of the two methods is more cost effective for estimating gross emissions from forest degradation due to mining. In this paper we: 1) describe and test two methods for estimating the area of forest degradation (i.e. AD) and the corresponding EFs from mining, 2), provide estimates of the total emissions from forest degradation adjacent to mining areas, 3) compare the efficacy of estimating emissions by these two methods, 4) compare the emissions from forest degradation with emissions from deforestation, and 5) recommend appropriate methods for moving forward in Guyana and other countries.

METHODS

Two different methods were developed for identifying the area of forest degradation (AD) in Guyana that results from mining activity. In the first method, a 100-meter buffer around identified deforestation areas due to mining (from the remote sensing work) was delineated in the GIS, and assumed that this is the area where forest degradation is likely to occur. A forest degradation analysis in Guyana of varying width buffers around deforestation using Landsat imagery was conducted by Salas et al. (2012) who found that most degradation occurred within 40 m of the edge of a mined area. Based on these results and further studies by the Guyana Forestry Commission (GFC) & Indufor (2012), a buffer size of 100 meters was chosen to adhere to principles of conservatism. This is a very basic approach that does not require in-depth spatial analysis, but also likely to overestimate the actual area of degradation.

To address potential shortcomings of just mapping the 100 m buffer around the mining infrastructure, a second method for determining the AD for degradation (GFC & Indufor 2015) was developed. This method identified evidence of forest degradation using 5 m resolution RapidEye multispectral satellite imagery, a set of established mapping rules, and 0.25 m resolution GeoVantage aerial imagery. This method potentially provides a more accurate estimate of the area of forest degradation, although it is time and labor intensive, and it is not always possible to distinguish between natural tree mortality and that caused by mine-related activity.

To estimate the change in forest carbon stocks, field data were collected from transects located in the forest. In the first method, transects were located across the whole width of the 100 m buffer around areas mapped as deforestation from mining, called non-mapped transects. In the second method, transects were located within polygons that were mapped as degradation, called mapped transects. The same measurements and field data were collected in transects for each of these methods.

Standard Operating Procedures (SOPs) were used to estimate the disturbance to the forest associated with mining. These procedures are described in the SOPs developed as part of the Forest Carbon Monitoring System

(FCMS) (Casarim et al. 2014) and are designed to assess the disturbance resulting from the mining activity, including tree removal, incidental damage, and forest floor disturbance.

Field and Remote Sensing Data

This study used data from temporal imagery, mapping, validation datasets, and data from ground surveys spanning 2010 to 2015 (Table 1). These data were used to locate candidate sampling sites and to estimate the impact of degradation from mining on the forest carbon stocks.

Table 1. List of data sets used for the mining degradation study

Data type	Data products	Period
Vector	Guyana forest map 2011 (year 2)	October 2010 – December 2011
	Guyana forest mapping 2012 (year 3)	January 2012 – December 2012
	Guyana forest mapping 2013 (year 4)	January 2013 – December 2013
Raster	5m-RapidEye Satellite Imagery	2011 - 2014
	0.25m-GeoVantage Aerial Imagery	July – August 2015
Ground survey	62 rectangular transects of 20m*100m (0.2 ha) each	July – August 2015

Sampling Design for Location of Field Transects

The sampling design took advantage of the availability of high resolution (5-m) RapidEye satellite imagery and very high resolution (0.25-m) GeoVantage aerial imagery. The location of potential sampling sites was established from the multi-temporal RapidEye imagery (2011-2014) that had been used to identify firstly deforestation and subsequent delineation of degradation based on manual interpretation (mapped in 2011, 2012, and 2013) surrounding the mining sites. The accuracy of the yearly deforestation mapping products was independently assessed (GFC and Indufor 2015), which has shown a very high level of accuracy (~99%). These potential sites were then filtered based on overlaying the 0.25-m GeoVantage aerial photos on the 5-m RapidEye imagery to confirm the occurrence of forest degradation around the mining sites. The 100 m wide buffers around the mining deforestation areas were also overlain onto these images. Field sites were then selected based on accessibility and on representation of mining operations (Figure 1). We identified five such areas and installed a total of 62 transects at these sites.

The sampling design for the two approaches is illustrated in Figure 2. This figure shows the two types of sampling areas—the non-mapped approach and the area around the mine where forest degradation was identified in the high resolution RapidEye imagery –the mapped approach. Transect locations were pre-established in these buffers (non-mapped) and degradation (mapped) polygons. The basic steps involved in sampling design are as follows:

1. Select location with concentration of mining over 4 years.
2. Select areas (polygons) with degradation and deforestation with mining as the driver of change.

3. Select degradation polygons that are adjacent to deforestation and large enough to enclose a 20 m by 100 m sample transect.
4. Fit mapped area transects into degradation areas mapped by GFC (random where possible).
5. Select non-mapped transects at random around deforestation polygons in the 100 m buffer as follows: from deforestation polygon centroid – note 8 cardinal points and chose 2 at random.

All potential transect locations were established on maps in advance of the field work.

The following methods were followed to determine specific transect location and lay out transects.

- With the non-mapped approach (in 100m buffers around the mining sites):
  - Coordinates were established at the intersection of deforestation and buffer, at 8 cardinal directions around deforested area (N, NE, E, SE, S, SW, W, NW).
  - Two transects in each non-mapped buffer were established at a randomly chosen cardinal direction. If a transect was inaccessible for reasons of safety, the next randomly chosen location was selected until 2 transects were measured. The transect length must extend the full 100 m across the buffer. If for some reason the whole 100 m cannot be measured, then another randomly chosen transect must be selected.

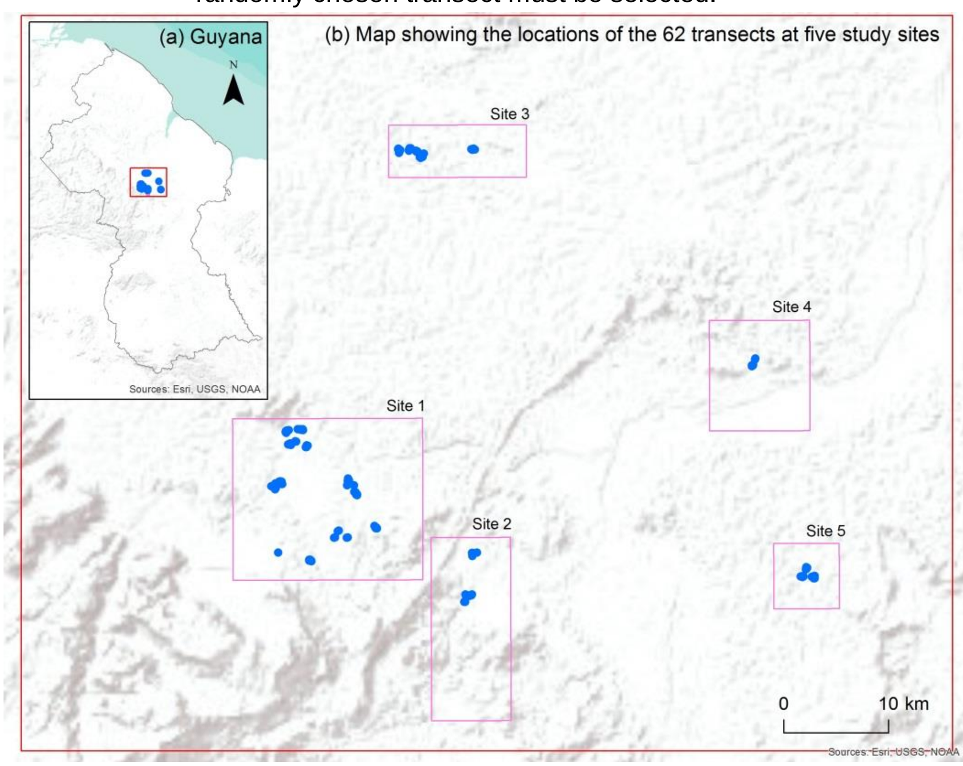

Figure 1. Map showing the locations of five mining sites that were selected based on accessibility and representation of mining operations.

    - Transect should run perpendicular to the mine across the whole width of the buffer (100 m) and 20 m wide, with 10 m distance either side of the central line.
- With the mapped approach:
    - Start point and end point for each transect were pre-established within polygons, with transect running parallel to the long side of the polygon (see Figure 3 left).
    - Transects were the same width as those for the non-mapped transects.
- For each method, the field team navigated to the start point (point closest to the deforestation area) and recorded latitude/longitude with a GPS of actual starting location.
- The transect line was established by navigating to the pre-established ending location (must equal 100 m long), tracking the transect along the way.
- Photos are taken at the start, middle, and end of the transect and photo numbers recorded.

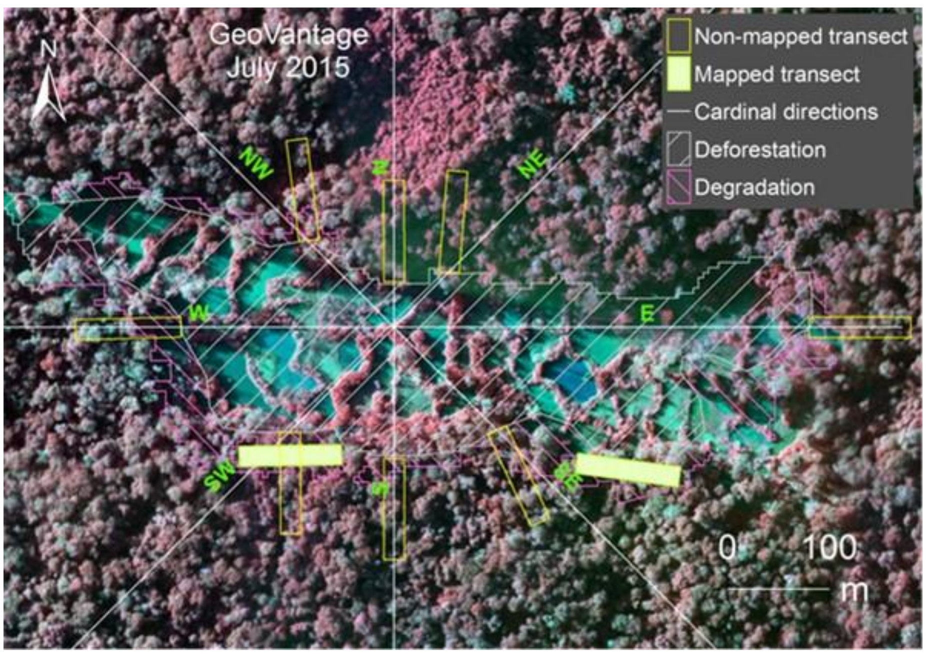

Figure 2. Example of a mined area, with pre-selected locations for degradation transects. The rectangles outlined in yellow show the potential locations of transects established within the non-mapped buffer and the solid yellow rectangles show transects located within the mapped polygons.

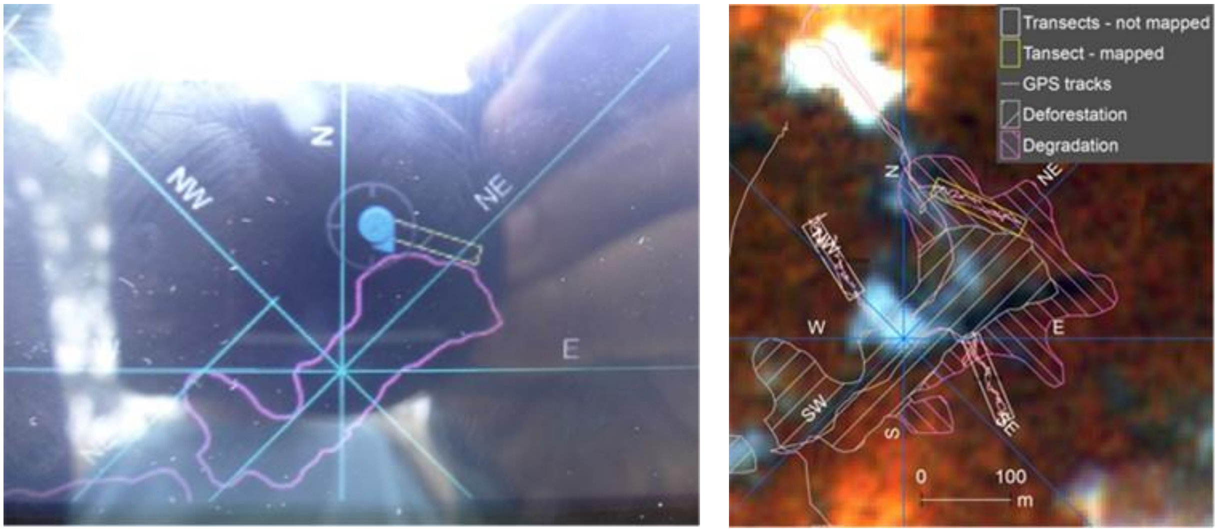

Figure 3. Process of transect tracking using a Garmin Montera GPS (left) and processing in a GIS using ArcMap 10.3 (right) using the survey data.

Sampling Design for Field Data Collection

The field measurements and data collection were the same for each method and transect. The following procedures were followed for data collection in all transects.

Identify all tree mortality or damage

- Measure all damaged trees (lying and standing) ≥10cm dbh or basal diameter at 5 cm aboveground (when dbh is not measureable) and record the species where known, otherwise record unknown.
- Measure distance from start of transect to damaged tree (X and Y coordinates).
- Note likely cause for all damaged trees into two classes:
    - those trees whose mortality was, based on expert opinion of the field team, due to human impact from the mining activities—e.g. cutting, snapped, broken, washed out roots, root burial by sediments, trail construction, flooding, or presence of toxic mining waste;
    - those trees whose mortality was due to natural causes.

Identify other evidence of degrading activities.

- Map and measure distance from starting point
- Note likely activity/cause (e.g. associated trails)
- Describe disturbance

Above ground biomass measurements

- Record the dbh and species of all live trees ≥10 cm dbh along the transect
- Record location of the measured trees by noting the cell (10 m × 10 m grid) in which they are located.

The field data collection was conducted in July and August of 2015. The number of transects established by plot type and in each site is given in Table 2.

Table 2. Distribution of the 62 transects by year and type

Year	# of transects		
	Mapped	Non-mapped	Total
2011	6	11	17
2012	8	16	24
2013	7	14	21
Total	21	41	62

Data Analysis

Estimation of carbon stocks in aboveground biomass

Tree data from all transects were converted to aboveground biomass using an equation from Chave et al. (2005) that estimates biomass for moist forests using diameter at breast height and wood density (Eq. 1). Estimates of below ground biomass are not included in this analysis.

$$AGB_{est} = \rho \times \exp(-1.499 + 2.1481 \times \ln(D) + 0.207 \times (\ln(D))^2 - 0.0281 \times (\ln(D))^3) \ldots\ldots\ldots\ldots (Eq. 1)$$

Where:

AGB_{est} = above ground biomass, kg

ρ = species specific wood density, g/cm^3 (when not available an average value for Guyana of 0.65 g cm^{-3} was used)

D = diameter at breast height (dbh), cm

$\exp$ = "*e*" to the power of

$\ln$ = natural logarithm

Where the diameter was measured directly this was used in the Chave et al. equation. However, if the tree has been removed, the basal diameter was measured and the dbh was estimated using a taper factor (T_{taper}) (see Eq. 2):

$$D_{estimated} = D_{base} - \left[\left\{1.3 - \left(\frac{H_{base}}{100}\right)\right\} \times T_{taper}\right] \ldots\ldots\ldots \quad \ldots (Eq. 2)$$

Where: $D_{estimated}$ = Estimated diameter at breast height, cm

D_{base} = Basal diameter, taken at 5 cm above the ground; cm

H_{base} = Height of the basal diameter measurement, 5 cm

T_{taper} = Variation of unit of diameter over a unit of length; 0.79 cm m^{-1}, derived from previous field work on logging impact in Guyana (Casarim et al. 2014)

Aboveground biomass in kilogram was divided by 1000 to convert to Mg, and was then converted to Mg per hectare using a scaling factor based on the total area of the transect (1 ha divided by 0.2 ha area of a transect =5). This was multiplied by the carbon fraction 0.47 to convert to Mg of carbon per hectare (Mg C.ha^{-1}).

Statistical analysis

A normal quantile plot of the estimated amount of carbon loss (Mg $C.ha^{-1}$) in the 62 transects shows a large tail at both ends (<25th and >90th percentiles), with the values within the 25th to 95th percentiles showing a deviation from the baseline for mining damaged trees (Figure 4a). Likewise, a central tendency test does not provide clear evidence that the carbon loss values (Mg $C.ha^{-1}$) have a normal probability distribution (Figure 4c). The cases for logarithmic, square root and reciprocal transformations of the carbon loss values of mining damaged trees in the 62 transects also did not satisfy the assumption of normality. The live trees show normality because the data points follow along the standard normal distribution line (Figure 4b & d).

Because the data for carbon loss by tree mortality due to mining or other causes is skewed and non-normally distributed, the median is considered a better measure of the central tendency of the data set. Given that the carbon loss values were not normally distributed, non-parametric statistical analyses were applied to the results of the field data. We note that the field measurements that took place in 2015 represent cumulative damage over several years (2 yr for 2013, 3 yr for 2012, and 4 yr for 2011) since first recorded in the imagery, as well as potential cumulative regrowth over these time periods.

The Wilcoxon (1945) rank-sum non-parametric test was used to test if the differences in carbon loss among years for each transect type were significant or not. For a sample size of n_1 from $X_1$and another of size n_2 from X_2, the Wilcoxon rank-sum test for the two independent random variables, $X_1$and X_2 based on the null hypothesis (H_0) $X_1 \sim X_2$ i.e. the mapped and non-mapped transects came from populations with the same median, the test statistic is:

$$z = \frac{T - E(T)}{\sqrt{Var\ (T)}} \ldots \ldots \ldots \ldots \ldots \ldots . (Eq. 3)$$

The Wilcox test was used to test the following hypotheses:

$$H_o: X_1 = X_2$$

$$H_1: X_1 \geq X_2 \ or \ H_1: X_1 \leq X_2$$

Where, sum of the ranks for the observation in the first sample using Wilcoxon test statistic

$$T = \sum_{i=1}^{n_1} R_{1i}$$

$$E(T) = \frac{n_1(n_1+1)}{2} \ldots \ldots \ldots \ldots \ldots \ldots (Eq. 4)$$

and $Var(T) = \frac{n_1 n_2 s^2}{n}$;

s = standard deviation of the combined ranks, r_i, for both groups:

$$S^2 = \frac{1}{n-1} \sum_{i=1}^{n} (r_i - \bar{r})^2$$

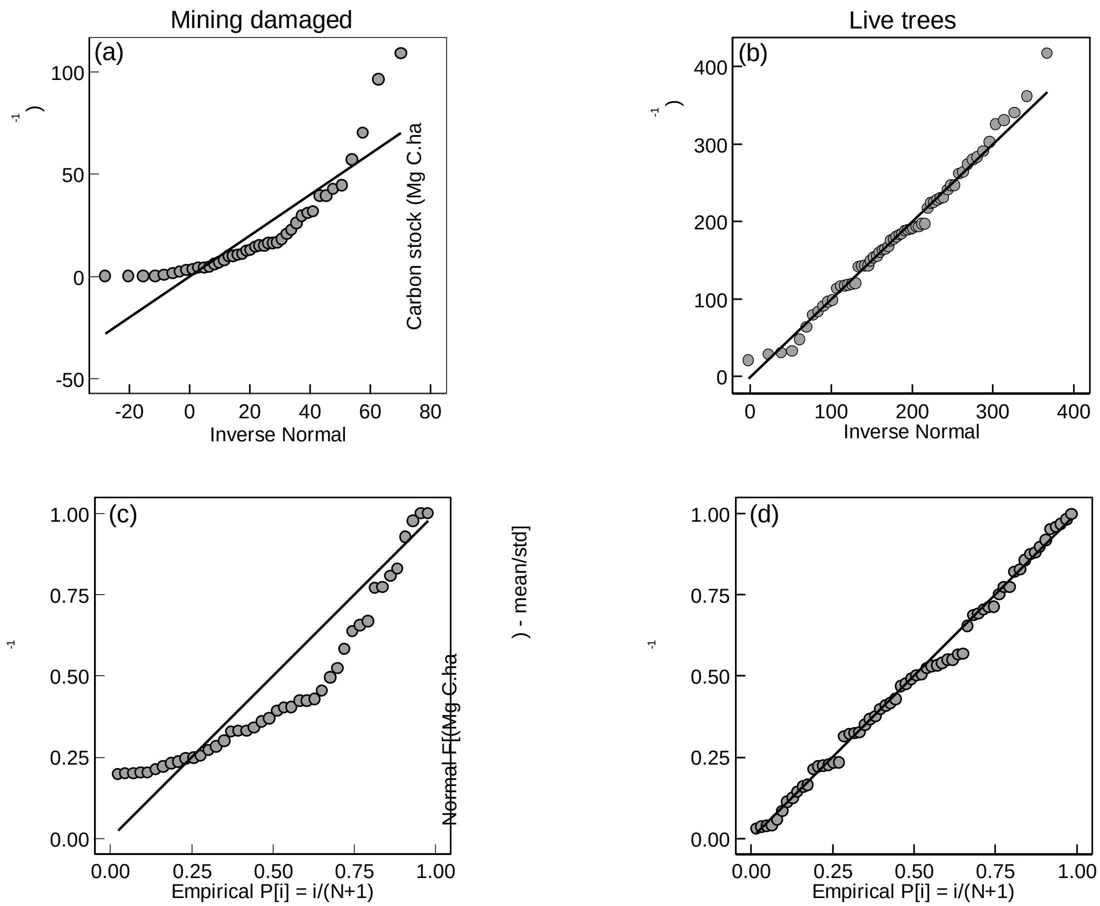

Figure 4. Distribution of quantile (a, c) of carbon loss of mining damaged trees and probability (b, d) of carbon stock in live trees of the 62 transects. If the data were normally distributed the data points would fall along the black solid line.

The test probability is computed as follows:

$$p = \frac{U}{n_1 n_3} \dots\dots\dots\dots\dots \quad .(Eq. 5)$$

Where, sum of the rank for the observations in the first sample $T = \sum_{i=1}^{n_1} R_{1i}$ and Mann and Whitney's (1947) U statistic is the number of pairs (X_{1i}, X_{2j}) such that $X_{1i} > X_{2j}$. These statistics differ only by a constant:

$$U = T - \frac{n_1(n_1+1)}{2} \dots\dots\dots\dots (Eq. 6)$$

RESULTS

About 4,206 tree stems were recorded in the 62 transects. Of these, tree mortality, expressed as a percentage of live trees recorded in the transects, due to mining activities was about twice as high in the mapped areas than in the non-mapped areas as expected. As expected also, tree mortality due to other causes (natural) was more or less the same in both areas (Table 3).

Table 3. Percentage of all recorded trees in the 62 transects that were damaged by mining activities or other causes.

Transect type	Mining damage	Other damage	All damage
Mapped	7.0%	3.7%	10.6%
Non-mapped	3.8%	4.1%	8.0%

Change in Carbon Stocks

The carbon loss due to tree damage from mining activities was variable and damage ranged from 0.0 to 109 Mg $C.ha^{-1}$ across all transects (Table 4). The highest carbon loss value of 109 Mg $C.ha^{-1}$ was found in one very disturbed mapped transect (mining disturbance along practically whole length of the transect next to a very active mining site) where two very large tree stumps of about 110 cm diameter were found near the end of the transect; these two trees alone accounted for about 90 Mg $C.ha^{-1}$ damage.

Because the results for carbon loss of damaged trees (both mining and other causes) were not normally distributed, the median value rather than the mean value is used in all further results and discussion. The median carbon lost per transect type and year ranged from 0.9 to 19.5 Mg $C.ha^{-1}$ (Table 4). The median loss in carbon stock across all years for the non-mapped transect was 2.2 Mg $C.ha^{-1}$ and for the mapped transect it was 13.0 Mg $C.ha^{-1}$ (Table 4).

Table 4. Summary statistics of carbon loss in mining damaged trees, in Mg $C.ha^{-1}$, in mapped and non-mapped transects.

Year	Transect type	# of transects	Min[m]	Max[m]	Median	95% Confidence interval Lower	Upper
2011	Mapped	6	0.0	19.4	7.3	0.0	19.1
	Non-mapped	11	0.0	57.1	4.3	0.0	16.1
2012	Mapped	8	0.0	109.3	19.5	2.0	66.0
	Non-mapped	16	0.0	70.3	0.9	0.0	8.4
2013	Mapped	7	0.0	39.5	8.2	0.0	37.0
	Non-mapped	14	0.0	96.7	8.5	0.0	19.0
	All Mapped	21	0.0	109.3	**13.0**	**1.4**	**21.1**
	All Non-mapped	41	0.0	96.7	**2.2**	**0.0**	**10.2**

Despite the different time periods over which the impact of mining occurred (2-4 yr), there were no significant differences in the carbon loss due to mining damage based on year for either transect type due to the high variability in the estimates (Table 5). That is, the null hypothesis for each transect type-- the carbon loss from damage in 2011 = 2012 = 2013—cannot be rejected.

In general, the mapped transects were found to have a higher percentage of mining damaged trees than the non-mapped transects (Figure 5). Most of the non-mapped transects (61%) lost 10 Mg $C.ha^{-1}$ or less in trees due to mining damage and this was dominated by the <1 Mg $C.ha^{-1}$ class (Figure 5). For the mapped transects, about

43% lost 10 Mg $C.ha^{-1}$ or less in trees due to mining damage and like for the non-mapped transects, most was in the <1 Mg $C.ha^{-1}$ class.

Table 5. Results of the Wilcoxon Rank-sum test (Mann-Whitney 1947) used for testing the null hypothesis for each transect type of: carbon loss from mining in 2011=2012=2013.

Transect type	Year	# of transects	Z value	Probability (p) value[a]
Non-mapped	2011	11	-0.684	0.494 (0.577)
	2012	16		
	2011	11	-0.139	0.889 (0.484)
	2013	14		
	2012	16	-0.838	0.402 (0.413)
	2013	14		
Mapped	2011	6	-1.493	0.135 (0.260)
	2012	8		
	2011	6	-0.290	0.772(0.452)
	2013	7		
	2012	8	0.813	0.416 (0.625)
	2013	7		

[a] Values in the parentheses are the probability for the transects in 1st year one is larger than the transects in the 2nd year.

The amount of carbon loss due to mining damage was on average about five times higher than damage due to other causes in the non-mapped transects, whereas the opposite trend was observed in the mapped transects (Table 6). However, the mortality by mining or other causes occurred over different time periods suggesting that annual rates range from approximately 0.3% to 1.7% per year for mining damage and 0.4% to 1.3% per year for other causes (estimated as the amount of carbon emissions divided by the aboveground carbon stock, expressed as percent, and assuming average time period of 4 yr). These mortality rates are within expected rates of natural mortality found for trees in tropical lowland forests of neighboring Venezuela (0.1-3.9 % per yr on a biomass carbon basis; Carey et al. 1994). The results also suggest that carbon loss caused by forest degradation from mining in Guyana occurs at a rate similar to that of natural mortality.

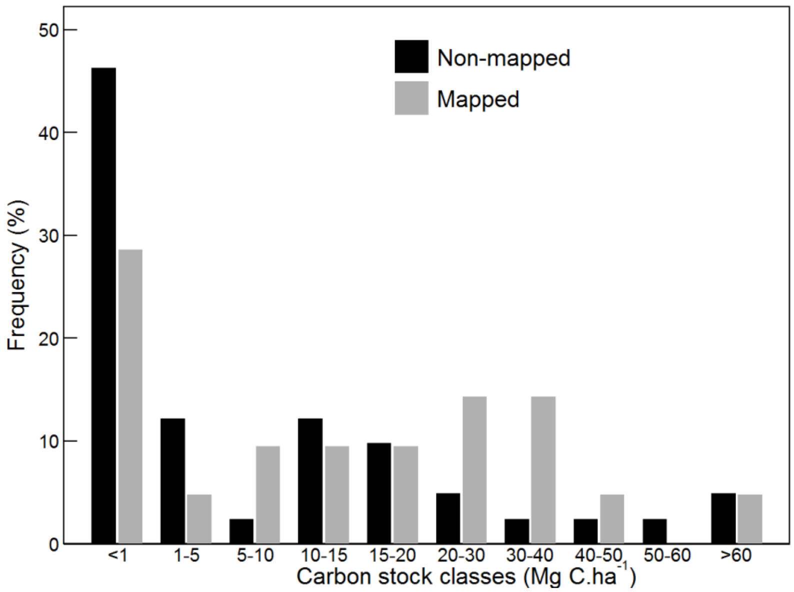

Figure 5. Frequency distribution of the C stock loss (Mg C. ha^{-1}) in trees damaged by mining for both transect types.

Although not the focus of this study, the estimates of the carbon stock in live trees from the transects (Table 6) are within the range of those obtained from the national forest carbon monitoring system (FCMS) for the high potential for change more accessible stratum (HPFC-MA) of 193.6 ± 19.9 Mg C ha^{-1} (mean and 95% CI).

Table 6. The mean carbon content in all live trees and the median carbon content in mining damaged trees and other damaged trees, all in units of Mg $C.ha^{-1}$, by transect type and by year.

Year	Transect type	Live tree[a]	Mining damage[b]	Other damage[b]	Above-ground[a] (live+all damage)
2011	Mapped	219.2	7.3	0.7	234.3
	Non-mapped	201.0	4.3	12.1	230.0
2012	Mapped	135.4	19.6	5.9	172.5
	Non-mapped	188.8	0.9	12.8	215.0
2013	Mapped	160.0	8.2	2.9	193.3
	Non-mapped	183.2	8.5	8.1	211.8
All Mapped		167.4 (±76.1)	13.0 (1.4-21.1)	2.9 (0.0-11.0)	197.1 (±44.6)
All Non-mapped		190.2 (±27.6)	2.2 (0.0-10.2)	11.6 (1.6-17.5)	218.0 (±29.4)

[a] -mean value for live trees with 95% CI in parenthesis; [b] –median for mining and other damaged trees with lower and upper bounds for 95% CI.

To address the question of how far along the non-mapped transects did mining damage occur, we plotted the distribution of the number of mining damaged stems and the associated C loss at 10 m intervals as a percent of all mining damaged trees and total carbon loss along the transect (Figure 6), starting from the edge of a deforestation polygon.

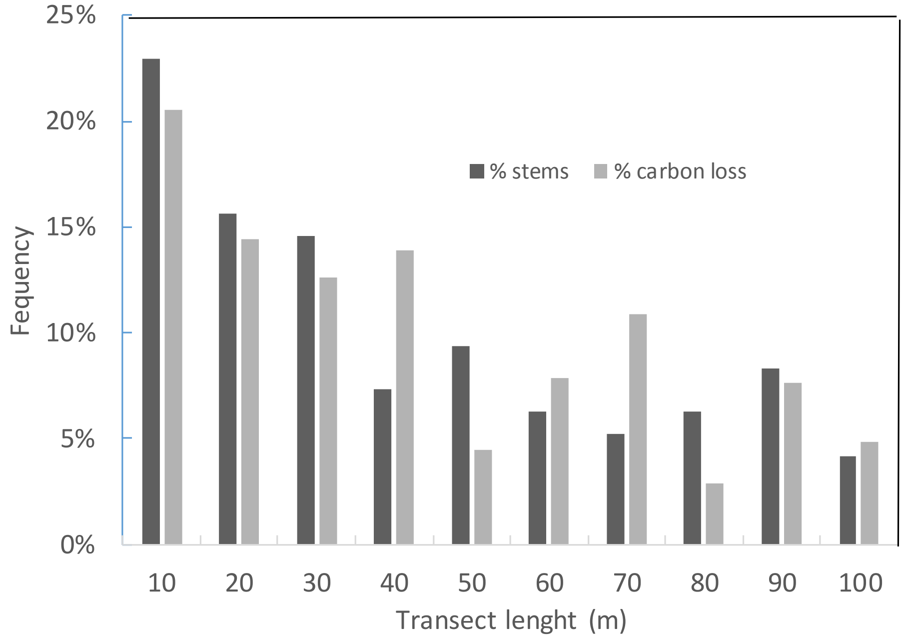

Figure 6. Distribution of stems and carbon loss from mining damage at 10m interval as a percent of all mining damaged trees and total carbon loss along the non-mapped transects.

The frequency (%) distribution of mining damaged stems in the non-mapped transects show an expected gradual decline with an increase in distance from the edge of the deforestation polygon (Figure 6). In the 42 non-mapped transects, about 70% of the mining damaged stems were located in the first half (0-50 m) of the transects whereas 60% of the carbon loss occurred in the same distance. At a distance of 80 m from the deforestation edge, 88% of the damaged stems and carbon loss occurred.

Emission Factors Compared to the Carbon Stock of Non-Degraded Forests

Under Guyana's National Forest Carbon Monitoring System (NFMS) (Brown et al. 2015), the country's forests have been stratified according to potential for change in forest cover (deforestation) and level of accessibility (six strata in all). A field sampling plan was developed and implemented to estimate biomass carbon stocks by each forest stratum in Guyana. The mined areas addressed in this report fall within the High Potential for Change More Accessible stratum (HPFC-MA). This stratum has aboveground live tree carbon stocks of 194 Mg $C.ha^{-1}$. Using the median EFs for mining degradation in the non-mapped transects of 2.2 Mg $C.ha^{-1}$, this equates to a loss of 1.1% carbon for the HPFC-MA. For the mapped transects, the median value of 13.0 Mg $C.ha^{-1}$ equates to a loss of carbon of 6.7% for this stratum.

Comparison of Emissions from Mining Degradation Based on the Two Methods

The non-mapped area of the 100 m buffers around the deforested areas caused by mining for each year 2011-2014 ranged from 31.5-51.2 thousand ha. The mapped areas of forest degradation due to mining for each of the same years (2011-2014) were more than an order of magnitude smaller, ranging from 2.4-3.2 thousand ha. The product of these areas and the appropriate EF, in terms of Mg $CO_2.ha^{-1}$, resulted in estimates of the annual emissions of CO_2 (Fig. 7). The average annual emissions for the non-mapped method were 322 thousand Mg CO_2, with a wide 95% confidence interval of 0-1,493 thousand Mg CO_2. For the mapped method, the average annual emissions were 134 thousand Mg CO_2, with a relatively narrow 95% confidence interval of 14-217 thousand Mg CO_2. The emissions for the mapped method were about a third lower than those for the non-mapped method even though the EF for the former was about six times higher than that for the non-mapped method.

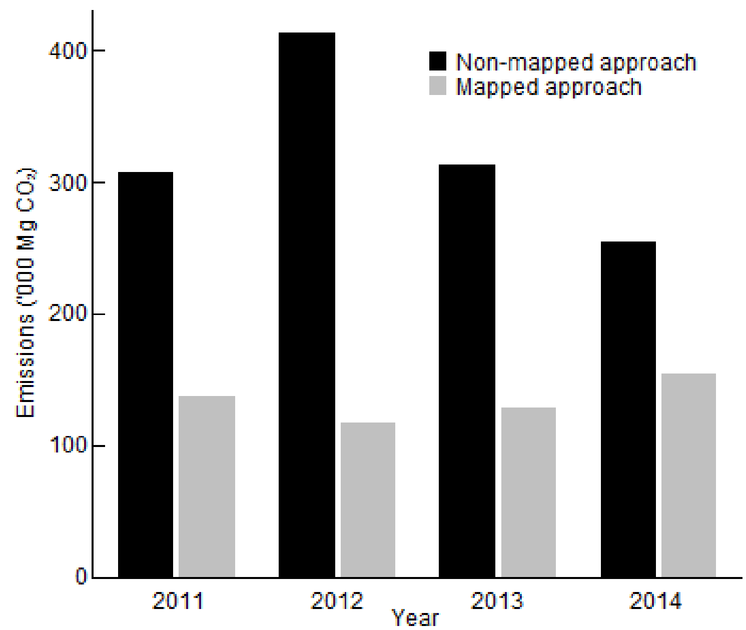

Figure 7. Carbon emission from forest degradation due to mining activities based on estimates of the emission factors from non-mapped and mapped approaches. The carbon emissions (Mg CO_2) are calculated from the Guyana Forest Commission yearly mapping data sets for areas mapped as mining degradation between 2011 and 2014.

DISCUSSION

The original Memorandum of Understanding (MOU) between the Governments of Norway and Guyana specified that the area of 500 m buffers around annual deforestation from mining be reported. In addition, they specified that 50% reduction of the carbon stock in these buffers would occur due to degradation. Analysis of remote sensing data has shown that there is clearly forest degradation associated with mining activity in Guyana, although the area impacted is much less than originally suggested in the MOU (Salas et al. 2012, GFC and Indufor 2012). The field work and data analysis described here also indicates that the magnitude of the loss in carbon stock due to mining activities in the 100 m buffers (non-mapped method) is also considerably less than the 50% loss as proposed in the MOU—losses of about 1% of the aboveground tree pool. In addition, the number of stems damaged and the carbon loss in the damaged trees due to mining activities is much higher within 0-50 m compared with the 50-100 m of the non-mapped transects.

How significant are these estimated emissions from forest degradation compared to total emissions from deforestation and total emissions from deforestation and logging in Guyana? A workbook was developed to estimate CO_2 emissions from deforestation, by all drivers, and selective logging as part of a larger project of providing assistance to the GFC on their REDD+ program, which was used in the development of Guyana's forest reference level (FRL) (Government of the Cooperative Republic of Guyana 2015). The workbook version used in developing the RL was updated to include all pools (the FRL included only above and below ground biomass carbon pool) and to extend the time to 2014. The average annual emission estimates from various sources for the period 2011-2014 are shown in Table 7.

It is clear that emissions from both approaches represent a small percent of the various emission sources. However, the percentage of emissions from the various sources represented by the mapped approach is about half that for the non-mapped approach. As mentioned above, the World Bank's Carbon Fund requires emissions from forest degradation to be accounted when they represent more than 10% of forest-related emissions. So under this condition, the emissions from degradation due to mining in Guyana would be considered insignificant no matter which approach was used.

Given the highly variable nature of the results, especially for the non-mapped approach, it is possible that the EF is really represented by the upper 95% CI. For the non-mapped approach, the use of the upper 95% CI results in average annual degradation emissions that are about 8% of those from all causes of deforestation plus logging, and would still be considered to be insignificant (are <10%). However, for the mapped approach, the average annual degradation emissions are about 1.2% of the emissions from all deforestation causes plus logging.

Table 7. Percentage of average annual (over period 2011-2014) emission sources represented by the estimated emissions from degradation around mining sites from the non-mapped and mapped approaches. The range of annual percentages is given in parentheses and the range is based on using actual annual total emissions for each year individually.

Emission source	Emissions (million Mg $CO_2.yr^{-1}$)	Non-Mapped (%)	Mapped (%)
Deforestation from mining only	12.0	2.7 (2.4-3.2)	1.2 (0.8-1.4)
Deforestation by all causes	14.4	2.2 (2.0-2.5)	1.0 (0.7-1.2)
Deforestation by all causes + logging	18.2	1.8 (1.5-2.0)	0.8 (0.6-0.9)

Given the small and insignificant impact of mining-caused degradation, it is argued that it is hard to make a case for the continuation of this monitoring process. The carbon impact of forest degradation presented here represents only the gross emissions and does not take into account how persistent the degradation might be or any regrowth and forest recovery—pioneer and small trees were observed in some of the year 2011 transects showing the ongoing recovery of forest growth, even while degradation is ongoing in other areas.

As described here, there is a great deal of effort involved in arriving at emission estimates from degradation around mining areas. For the mapped transect, the method requires manual mapping of degradation using 5m-RapidEye imagery and collecting field measurements of damage to develop EF in the mapped areas. An alternative approach of establishing 100 m buffers around mined areas involves no additional image interpretation, but does require field measurements as described in this paper to obtain EF. We found that the majority of transects in the 100 m buffer did not exhibit degradation throughout the whole length (only about 28% showed degradation along much of the 100 m transect). As we have shown, the area of the 100 m buffer is about an order of magnitude larger than the area of the mapped degraded polygons, and even though the EF for the 100 m buffer is considerably smaller than the mapped areas, it is likely that the emissions from the buffer approach overestimate the emissions from this forest change process.

The carbon impact of forest degradation presented here represents only the gross emissions and does not take into account how persistent the degradation might be or any regrowth and forest recovery. Inclusion of any regrowth would reduce the emissions even further to practically zero.

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