**Medium and Long Term Effects of Logging Systems on Forest Structure and Composition
in the tropical Rainforest of Suriname**

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Abstract (247 words)

In this study we compared the medium and long term effects of logging on tropical rain forest ecosystems in Suriname using reduced impact logging (RIL), CELOS Management System (CMS), and conventional logging (CL) with forest without logging (NAT). In 18 forest plots with different times since logging ended and 9 unlogged forest plots, assessments were conducted on indicators of forest structure and vegetation composition. These indicators were then modelled as a function of management type and plot age. Multivariate ordination was used to visualize forest structure and vegetation composition differences between plots. High vegetation cover in the tree layer was more related to the older RIL and the CL plots, while high vegetation cover in the sapling and seedling layer related more to the CMS and NAT plots. Canopy openness was more related to the NAT, the CMS and the younger RIL plots. Furthermore, the CMS plots, which were logged 30 years ago, still did not reach the basal area of commercially important primary forest species, compared to unlogged forest. Both RIL and CMS plots have a strong presence of secondary species. This study shows the importance of applying the RIL technique correctly and taking forest characteristics and ecological processes into account when developing forest management principles. Forest management systems should also be flexible enough to adapt to area specific requirements, for example, increasing the rotation cycle if the timber volume is not on the desired level. In this way, both conservation and economic goals are reached.

Keywords: forest dynamics, tropical rainforest, logging techniques, vegetation composition, forest structure

Introduction

Timber extraction remains one of the major economic activities in the Amazon region, and in other tropical rainforest regions in the world. Until today, the focus in these regions is mostly on extracting as much as possible during the first and often only harvest, in an uncontrolled way and with minimal to no forest management (Zarin et al. 2007; Putz et al. 2000). This method, also called conventional logging (CL), has led to the destruction and degradation of forest ecosystems all over the Amazon region and has made logging economically unsustainable on the long term (Macpherson 2010; Dauber et al. 2005; Putz et al. 2001). The introduction of reduced impact logging (RIL) was expected to lead to less damage to the forest ecosystem. It had to ensure timber production on the long term and has brought some hope for the forest sector (Putz et al. 2008; Johns et al. 1996). Across the tropical regions, this system is not yet incorporated in national policy frameworks and the adoption and implementation are often left to forestry companies (Dijkstra 2007). The main reason that this system is not widely adopted is that the benefits of RIL are not easy to prove (Martin et al. 2015). For certain forest aspects, individual studies have proven that RIL has fewer negative effects than CL (for example: carbon emissions: Pinard and Putz 1996; Putz et al. 2008; West et al 2014; residual tree damage: Sist et al. 2003; tree growth: Schwartz et al. 2014; fauna diversity: Bicknell et al. 2014). However, these studies are not sufficient for a generalization about the preference of RIL above CL (Martin et al. 2015; Osazuwa et al. 2015; Villela et al. 2006). Furthermore, knowledge on tropical forest dynamics and their response to logging systems require long term studies to detect patterns, which are needed to develop optimal forest management systems, including the next harvesting regimes for commercial tree species. Suriname, where this study was done, is also in the process of implementing RIL as the national logging system.

59 Suriname, located at the north coast of South America, bordered by Guyana in the west, French-
60 Guiana in the east and Brazil in the south, started with forestry activities even before the 1900s.
61 Logging occurs through what is called in Suriname, extensive logging, either through controlled
62 CL, where there is some form of planning involved, or through CL without any form of planning.
63 There are also some companies that extract timber using RIL with and without Forest Stewardship
64 Council (FSC) certification.

65 The Center for Agricultural Research in Suriname (CELOS) developed the CELOS Management
66 System (CMS) between the 1970s and the 1980s (Wegner 2011). It includes several aspects, such
67 as skid trail planning and pre-harvest inventory, and has set the basis for the RIL guidelines (Putz
68 et al. 2008). Aspects of the CMS are also incorporated in the controlled extensive logging system.
69 With its 93% forest cover, Suriname has the intention to maintain this status by committing itself
70 to develop and implement a national sustainable forest management system, which benefits both
71 timber extraction and conservation of the forest ecosystem on the long term (UNIQUE 2016). Data
72 on the effect on both CL and RIL are therefore needed to find an optimal forest management
73 system.

74 The objective of this study is to increase the knowledge regarding the benefits of implementing
75 RIL above other logging systems applied in the region, such as CL and CMS. This study makes
76 use of the available mosaic of forests in the Forestry Belt of Suriname to study the medium and
77 long term (medium: up to 10 years; long term: from 10 years on) effects of logging, when a forest
78 management system (CMS and RIL) was applied as well as when no forest management system
79 was applied (CL). These effects are also compared to forests where no logging was conducted. We
80 studied logging effects on forest structure and vegetation composition variables, using forest plots
81 with different times since logging.

Materials and Methods

Study area and logging history

The study was conducted at two sites in the Forestry Belt of the north-west of Suriname: 1. at the Suma Lumber Concession in the Tibiti area (N5°9'28.2", W55°54'13.5") and 2. the Tonka experimental research site (N 5°15'59.1", W 55°45'20.4") in the Kabo forestry concession. These areas are somewhat elevated (10 to 50 m above sea level) and are covered with mesophytic forest. The climate in the area is characterized as Af according to the Köppen-Geiger classification. Suma Lumber started its activities in primary forest in the Tibiti area in 1998. This concession area is divided in cutting blocks of 1250 x 800 meter (see Figure 1). Timber extraction started in 2004 using CL practices. In 2006, the first cutting block was logged according to RIL practices. In June 2008, the company received the Forest Stewardship Council (FSC) certificate. Extraction intensities with the CL practices were unfortunately not systematically documented. A target of 25 m³/ha was set, which has not been exceeded, since harvest at that time only focused on the biggest commercial trees and the easily accessible trees. During the RIL practices, the same target of 25 m³/ha was set and was also never reached, however, the extraction of trees was more uniformly planned in the cutting blocks. Commercial species were identified as target species for both the CL and the RIL practices and were felled with a chain saw, following directional felling principles for the RIL practices.

The Tonka experimental research site was set up in 1980 to investigate vegetation distribution patterns, the effects of logging and refinement on the forest and the efficiency of the CMS in terms of revenues (Jonkers 1987). For the experiment, 3 replication blocks were set up, each consisting of 9 plots of 2.25 ha. In addition, 3 plots within virgin forest have been selected as control plots by Jonkers (see Figure 1). One year after the first harvest, Jonkers started a factorial block

experiment with two factors and three levels: logging (with approximately 15, 23 or 46 m³/ha) felled and silvicultural treatments (no logging, refinement with 30 cm dbh limit, refinement with 20 cm dbh limit). For the logging practices, commercial species were targeted, which were felled with a chain saw. In the refinement lianas were cut and undesirable trees, which consisted of non-commercial species, over mature and poorly formed commercial tree species, were poison-girdled with and arboricide (Jonkers 1987). For details on the silvicultural treatment, see Jonkers (1987).

Figure 1

Study design

In the Suma Lumber Concession, five RIL cutting blocks and two CL cutting blocks were selected. Nine 100 x 100 m plots were randomly placed in the RIL cutting blocks (hereafter called RIL plots) and six 100 x 100 m plots in the CL cutting blocks (hereafter called CL plots). Plots were logged at different times (RIL plots logged in 2006, 2007, 2008, 2009 and 2014; CL plots logged in 2006) and thus resulted in plots with different times since logging. Besides these plots, six 100 x 100 m plots were randomly placed in adjacent natural forest blocks, where no logging has been carried out (hereafter called NAT plots).

In the Tonka experimental site, three 100 x 100 m plots (hereafter called CMS plots) were set up in the 2.25 ha experimentally logged plots with a logging intensity of 46 m³/ha and refinement with 20 cm dbh limit (plot 16, 24 and 39 in Figure 1). Three undisturbed plots in adjacent forest were also selected (hereafter also called NAT plots) to function as control plots and are approximately 50 m apart from each other (plot 41, 42 and 43 in Figure 1).

In each 100 x 100 m plot (used for tree assessments), sixteen 10 x 10 m plots were set up. In these 10 x 10 m plots, one 5 x 5 m plot (used for sapling assessments) and one 2 x 2 m plot (used for forest structure variables and seedling inventory) were set up (Figure 2).

Figure 2

Sampling

Forest structure assessment

For the forest structure assessment, the habitat characterization of Rödel & Ernst (2004) was used, complemented and adapted to the local situation. Compared to the characterization of Rödel & Ernst (2004), we did not determine the substrate, since we did not expect to find much variation on the micro scale. Furthermore, we adapted the shrub layer from 0.5-1.5 to 0.5-3.0m and added canopy openness as a forest structure variable. Forest structure variables measured in the sixteen 2 x 2 m plots were: vegetation % cover in different strata (understory (<0.5 m), shrub (0.5-3 m), lower tree (3-20 m) and canopy layer (>20 m)), which was determined by visually classifying each stratum (1 = absent; 1.5 = transition; 2 = gaps predominating; 2.5 = transition; 3 = closed area predominating; 3.5 = transition; 4 = closed). Litter cover was also determined by classifying the % litter covered (1 = 0-20%; 2 = 21-40%; 3 = 41-60%; 4 = 61-80%; 5 = 81-100%). Canopy openness, here defined as the portion of the sky hemisphere that is not obscured by vegetation elements viewed from a point (Jennings et al. 1999), was measured using hemispherical photographs taken with a Nikon D300s camera with a 14 mm F/2.8 fish eye lens and analyzed with the Gap Light Analyzer software (Fraser et al. 1999). Sampling in the Tonka experimental site was done from 2012 to 2013 and in the Suma Lumber Concession area from 2015 to 2016.

Vegetation composition assessment

The vegetation composition inventory includes an assessment of (young) trees, saplings and seedlings. At both sites, all trees above 15 cm diameter at breast height (DBH) were assessed in

the 100 x 100 m plots. From trees above the indicated minimum DBH, the height and DBH were measured and the tree species identified. Saplings, which are defined as that part of the vegetation with DBH between 1 and 5 cm and a height maximum of 2 m, were counted in each 5 x 5 cm plot and identified. Also, in both study areas, seedlings, which are defined as that part of the vegetation with a maximum height of 20 cm, were measured. Seedlings were counted in each 2 x 2 m plot and identified. In the Suma Lumber Concession, also young trees (between 5 and 15 cm DBH) were assessed (height and DBH) in the 100 x 100 plots and identified using local names. Young trees were not included in the assessment protocol for the Tonka experimental site and so therefore not assessed.

Vegetation composition was then characterized as either primary or secondary forest species using the habitat description of van Roosmalen (1985). Species were also classified as commercial timber, protected or non-commercial species using the listed species per category mentioned in the Forest Management Act (1992) of Suriname. These vegetation traits were used to calculate community-weighted means and the basal area per characteristic. Lianas were excluded from the analysis due to insufficient knowledge about their taxonomy and based on the information from previous studies that the abundance of countable specimens was too small to be included in the data analyses (Jonkers 1987). Sampling in the Tonka experimental site was conducted from 2012 to 2013 and in the Suma Lumber Concession area from 2015 to 2016.

Data analysis

In all analyses, both sites were taken together, except when the young trees were involved. The 100 x 100 m plot was used as the unit of analysis for vegetation composition; 100 x 100 m plot averages were used for forest structure analysis. Non-metric multidimensional scaling (NMDS)

173 was used to visualize and explore the effect of management type (RIL, CL, CMS or NAT) on the
 174 forest structure variables (vegetation % cover; litter cover; canopy cover fraction) and on
 175 vegetation composition (as matrix with species abundances).
 176 Generalized linear mixed modelling (formula for GLMM: $Y = X\beta + Z\mu + \epsilon$) was used to test the
 177 effect of management type (RIL, CL, CMS or NAT) and the categorized plot age (1: 3 years, 2:
 178 year 7-8, 3: year 9-10, 4: 10-30, 5: >30 years) as fixed effects (X) on the observed variables (Y),
 179 being forest structure variables (vegetation % cover; litter cover; canopy cover) and vegetation
 180 composition variables (species and functional diversity indices). As random factors (Z), the plot
 181 and the cutting blocks were used. Significant testing of explanatory variables was done by using
 182 the Wald test with adjusted degree of freedom (Zuur et al., 2009; Kenward and Roger, 1997).
 183 The species diversity indices (Shannon, Simpson, # of species, # of families) were calculated
 184 according to Krebs (1999); # of species and # of families were also calculated per vegetation layer.
 185 The community-weighted mean (CWM) for functional diversity indices was calculated according
 186 to the formula: $\sum W_i * X_i$, with w_i as the abundance of species i and x_i as the trait value for species
 187 i .
 188 Two CWM indices were calculated: 1. the integrity community-weighted mean (CWM integrity
 189 index), which is the weighted average of secondary forest species over primary forest species; the
 190 presence of secondary species is positively related to the inverse of the community-weighted mean.
 191 2. the provisioning community-weighted mean (CWM provisioning index), which is the weighted
 192 average of non-commercial species over commercial species and species protected by law; the
 193 presence of non-commercial species is positively related to the inverse of the provisioning
 194 community-weighted mean. The inverses of these community-weighted means were then used in
 195 the glmm analyses.

Data analysis was done by using the softwares InfoStat (Di Rienzo et al., 2016) and R, version 3.0.1 (R Core Team 2013), using the packages nlme and vegan.

Results

NMDS ordination of forest structure variables (Figure 3a) reveals a correlation between high canopy openness and some of the NAT plots (NAT4-6), CL plots (CL1, CL3, CL6), CMS plots (CMS1, CMS3) and some of the younger RIL plots (RIL7, RIL8). Vegetation cover in the vegetation layer < 3 meter is more related to some the NAT (NAT4, NAT6 and NAT7) and the CMS plots. Vegetation cover in the vegetation layer >3 meter is more related to most of the RIL plots (RIL1-6, RIL9), some of the CL plots (CL2, CL4 and CL5) and some of the NAT plots (NAT 1-3). The first axis of the NMDS ordination for the vegetation composition in Figure 3b divides the plots based on the two areas (Tonka experimental site: CMS1-3, NAT7-9; Suma Lumber Concession area: RIL1-9, CL1-6, NAT1-6). The second axis divides the plot based on time since logging, having the oldest plots on one side and the youngest plots, which are the RIL plots (RIL7-8), together with their pre-disturbed counter plots (NAT4-6), on the other side.

Since the forest structure variables cannot clearly relate to a management type, individual inspection of forest structure and vegetation composition variables is used to give more insight in patterns. Table 1 gives an overview of the most important effects of management type on forest structure variables and vegetation composition, determined with the GLMM. Table 2 gives an overview of the most important effects of plot age on forest structure variables and vegetation composition, determined with the GLMM. The effects of forest management systems and plot age on all variables can be found in the Supplementary Material.

Figure 3.

Table 1

Table 2

Discussion

Effect of management systems on forest structure and composition

Logging had, as expected, an overall significant effect on the forest structure variables measured (see Table 1). We predicted that these effects would have been less pronounced in the RIL plots, even when dealing with CL plots that are older and had more time to recover. However, for canopy openness both high and low numbers were found in the RIL plots, which were on average still significant lower than the other plots. High numbers were found for vegetation cover in the lower tree stratum and high secondary species basal area in the RIL plots. Contrary to the RIL guidelines, the high canopy openness created by the logging activities, resulted in the opportunity for secondary forest species establishment. This may be the result of incorrect implementation of the RIL technique, which was also observed in RIL operations in Bolivia and which resulted in suggestions for improved application, including training of felling personnel on a regular basis and close supervision during felling activities (Jackson et al. 2002). The CMS and the NAT plots were expected to have a more closed canopy and trees with a bigger tree diameter in the canopy layer. But unexpectedly, even the canopy in the Tonka experimental site, where the CMS method was practiced, showed elevated canopy openness. These open canopies are associated with a dense palm layer in the understory with some smaller canopy trees in between, which resulted in plots having naturally a more open canopy (Jonkers, 1987). For the vegetation composition, the NMDS clearly distinguished plots from each other, firstly on local vegetation diversity and secondly on logging effects. This diversity may be due to spatial heterogeneity, which is considered as one of

the major forces behind the stability that Amazon rainforests show and which makes them resilient against, for example, climate change effects. High intensity logging, which may lead to a decrease in tropical forests' heterogeneity, can undermine this resilience and may even increase the effects of climate change on these forests (Levine et al. 2016).

For the effect of logging on vegetation composition, contrasting results are seen in our study, such as high species diversity indices in the logged plots (Table 2). The interaction between changes in forest structure variables, such as canopy openness, and forest dynamics, remain the crucial source to explain logging effects and predict recovery. As the forest is being opened by felling and removing timber, increased sunlight on the forest floor stimulates regeneration and may thus increase species diversity, causing even for logged plots to have high species diversity (Ashton, 2008). However, studying the effects of logging only based on species diversity indices may give an incomplete insight in the effect of logging on vegetation composition, because these indices do not give any information on what type of vegetation in the regeneration contributes to the high species diversity. Since it is known that increased sunlight favors the regeneration of pioneer species, we addressed this complication by also looking at the ratio between shade-intolerant and shade-tolerant species using the inverse CWM integrity index. The results of the GLMM analyses show that the index did not differ between management types, but differed significantly with age, in which the younger logged plots have a higher secondary species abundance than the older plots (Table 2). As the regeneration of pioneer species is more related to forest gap area (Landburg 2016), it seems that the CWM integrity index calculated on a forest management unit decreases with forest gap area. In case gap area and density increase, so will the regeneration of secondary species and therefore the CWM integrity index will decrease.

Medium and long term effects

In spite of the longer recovery time of the CL plots, minimal differences were detected in the forest structure variables between the RIL and the CL plots. This indicates that the CL plots were seriously affected during the logging activities. It is therefore possible that these medium term effects may turn into long term effects. This can also be concluded for the changes in the vegetation composition due to logging. According to the gap phase theory, secondary forest species do not last in the forest ecosystem and will be replaced by more primary forest species over time (Aravena et al. 2002). As proven by other studies, this time can be very prolonged and can vary up to 100 years (García-Flórez et al. 2017; Kukkonen and Hohnwald 2009; Hall et al. 2003, Boscolo and Vincent 2000). A combination of extreme extraction and silvicultural treatment levels executed by the CMS in the Tonka experimental site, and forest dynamics, resulted in the extensive influx of secondary species, such as *Cecropia* spp. and *Inga* spp. in these plots, which are still evident approximately 30 years after logging. The CWM integrity indices of these plots were therefore significantly lower and the basal area of secondary forest species in these plots were significantly higher, compared to the natural forest. Approximately 30 years after logging, which is longer than the rotation cycle of 25 years set for these plots, the basal area of commercially interesting species is still not up to the level of the basal area of these species in primary forest in the same area. It is thus clear that the determined rotation cycle does not coincide with the recovery timeline of these forests. The use of rotation cycles that are too short and not aligned with the recovery time of the forest, is one of the reasons why projections of harvesting volumes over time keep decreasing (van Gardingen et al. 2006), and the forestry sector is being seen as not sustainable on the long term.

Management implications

It is important to implement the RIL logging techniques correctly in the field and make use of skilled and trained personnel in doing so. Only then the benefits of RIL on the forest and compared to CL will be visible. The characteristics of the forest unit to be harvested should be taken into account when developing management principles, including forest dynamics and ecological processes, to avoid long term and irreversible effects on the forest. Furthermore, forest management systems should be flexible enough to adapt management principles to area specific requirements, such as increasing the rotation cycle if the required timber volume for the next harvest has not been reached yet. In this way, both conservation and economic goals for the forest unit are reached.

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References

1. Aravena JC, Carmona MR, Pérezi CA, Armesto J. 2002. Changes in tree species richness, stand structure and soil properties in a successional chronosequences in northern Chiloé Island, Chile. *Rev Chil Hist Nat.* 75: 339-360.

2. Ashton PS. 2008. Changing values of Malaysian forests: the challenge of biodiversity and its sustainable management. *J Trop For Sci.* 20 (4): 282-291.
3. Bicknell J, Struebig M, Edwards D, Davies Z. 2014. Improved timber harvest techniques maintain biodiversity in tropical forests. *Curr: CB.* 24. R1119-20. DOI: 10.1016/j.cub.2014.10.067.
4. Bertault JG, Sist P. 1997. An experimental comparison of different harvesting intensities with reduced impact and conventional logging in East Kalimantan, Indonesia. *For Ecol Manag.* 94: 209-218.
5. Boscolo M, Vincent JR. 2000. Promoting better logging practices in tropical forests: a simulation analysis of alternative regulations. *Land Econ.* 76 (1): 1-14.
6. Dauber E, Fredericksen TS, Peña M. 2005. Sustainability of timber harvesting in Bolivian tropical forests. *For Ecol Manag.* 214: 294-304.
7. Deckker M, de Graaf NR. 2003. Pioneer and climax tree regeneration following selective logging with silviculture in Suriname. *For Ecol Manag.* 172: 183-190.
8. Degen B, Blanc L, Caron H, Maggia L, Kremer A, Gourlet-Fleury S. 2006. Impact of selective logging on genetic composition and demographic structure of four tropical tree species. *Biol Conserv.* 131: 386-401.
9. Diaz S, Cabido M. 2001. Vive la difference: plant functional diversity matters to ecosystem processes. *Trends Ecol Evol.* 16: 646-655.
10. Dijkstra DP. 2007. Promoting Reduced-Impact Logging in tropical developing countries: a success story of technology transfer. In: Miner C, Jacobs R, Dijkstra D, Bittner B, editors. *Proceedings of the International conference on transfer of forest science knowledge and*

- technology. Gen. Tech. Rep. PNW-GTR-726. Portland, OR: U.S. Department of
Agriculture, Forest Service, Pacific Northwest Research Station, p. 139-147.
11. Di Rienzo JA, Casanoves F, Balzarini MG, Gonzalez L, Tablada M, Robledo CW. 2016.
InfoStat version 2016. Grupo InfoStat, Universidad Nacional de Cordoba, Argentina.
12. Fraser GW, Canham CD, Lertzman KP. 1999. Gap Light Analyzer (GLA): Imaging software
to extract canopy structure and gap light transmission indices from true-colour fisheye
photographs, user's manual and program documentation. Simon Fraser University, British
Columbia.
13. Garcia-Florez L, Vanclay J, Glencross K, Nickols JD. 2017. Understanding 48 years of
changes in tree diversity, dynamics and species responses since logging disturbance in a
subtropical rainforest. *For Ecol Manag.* 393: 29-39.
14. Hall JS, Harris DJ, Medjibe V, Mark P, Ashton S. 2003. The effects of selective logging on
forest structure and tree species composition in Central African forest: implications for
management of conservation areas. *For Ecol Manag.* 183: 249-264.
15. Jackson SM, Fredericksen TS, Malcolm JR. 2002. Area disturbed and residual stand damage
following logging in a Bolivian tropical forest. *For Ecol Manag.* 166: 271-283.
16. Jennings SB, Brown ND & Sheil D. 1999. Assessing forest canopies and understorey
illumination: canopy closure, canopy cover and other measures. *Forestry.* 72 (1): 60-73.
17. Johns JS, Barreto P, Uhl C. 1996. Logging damage during planned and unplanned logging
operations in the eastern Amazon. *For Ecol Manag.* 89: 69-77.
18. Jonkers WBJ. 1987. Vegetation structure, Logging Damage and Silviculture in a Tropical
Rainforest in Suriname [dissertation]. Wageningen: Agricultural University.

- 355 19. Kenward MG, Roger JH. 1997. Small sample inference for fixed effects from restricted
356 maximum likelihood. *Biometrics* 53: 983-997.
- 357 20. Krebs CJ. 1999. *Ecological methodology*. 2nd ed. Addison-Wesley Educational Publishers,
358 Menlo Park.
- 359 21. Kukkonen M, Hohnwald S. 2009. Comparing floristic composition in tree fall gaps of
360 certified, conventionally managed and natural forests of northern Honduras. *Ann. For. Sci.* 66
361 (8): 1-8.
- 362 22. Landburg G. 2016. Reduced impact logging affects forest gaps less than conventional logging
363 and natural tree fall. Paper presented at: 4th International Biodiversity Conference of the
364 Guiana Shield; August 8-11; Georgetown, Guyana.
- 365 23. Levine NM, Zhang K, Longo M, Baccini A, Phillips OL, Lewis SS, Alvarez-Dávila E, Segalin
366 de Andrade AC, Brienens RJW, Erwin TL, et al. 2016. Ecosystem heterogeneity determines
367 the ecological resilience of the Amazon to climate change. *PNAS*. 113 (3): 793-797.
- 368 24. Luna AC, Osumi K, Gascon AF, Lasco RD, Palijon AM, Castillo ML. 1999. The community
369 structure of cagedover tropical rain forest in Mt. Makiling Forest Reserve. Philippines. *J Trop*
370 *For Sci.* 11: 446-458.
- 371 25. Macpherson AJ, Schulze MD, Carter DR, Vidal E, 2010. A model for comparing reduced
372 impact logging with conventional logging for an Eastern Amazonian Forest. *For Ecol Manag.*
373 260: 2002-2011.
- 374 26. Magnusson WE, de Lima OP, Reis FQ, Higuchi N, Ramos JK. 1999. Logging activity and
375 tree regeneration in an Amazonian forest. *For Ecol Manag.* 113: 67-74.

27. Martin PA, Newton AC, Pfeifer M, Khoo M, Bullock JM. 2015. Impacts of tropical selective logging on carbon storage and tree species richness: A meta-analysis. *For Ecol Manag.* 356:224-233. 10.1016/j.foreco.2015.07.010.
28. Okuda T, Suzuki M, Adachi N, Quah ES, Hussein N, Manokaran N. 2003. Effect of selective logging on canopy and stand structure and tree species composition in a lowland dipterocarp forest in Peninsular Malaysia, *For Ecol Manag.* 175: 297-320.
29. Osazuwa-Peters OL, Jiménez I, Oberle B, Chapman CA, Zanne AE. 2015. Selective logging: Do rates of forest turnover in stems, species composition and functional traits decrease with time since disturbance? – a 45 year perspective. *For Ecol Manag.* 357:10-21. DOI: 10.1016/j.foreco.2015.08.002.
30. Pinard AM and Putz EF. 1996. Retaining Forest Biomass by Reducing Logging Damage. *Biotropica.* 28: 278-295. doi:10.2307/2389193
31. Putz FE, Redford HK, Robinson J, Fimber R, Blate GM. 2000. Biodiversity conservation in the context of tropical forest management. The World Bank Environment Department.
32. Putz FE, Blate GM, Redford HK, Fimber R, Robinson J. 2001. Tropical forest management and conservation of biodiversity: an overview. *Biol Conserv.* 15 (1): 7-20.
33. Putz FE, Sist P, Fredericksen T, Dykstra D. 2008. Reduced impact logging: Challenges and opportunities. *For Ecol Manag.* 256: 1427-1433.
34. R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. URL: <http://www.R-project.org/>.
35. Rödel MO, Ernst R. 2004. Measuring and monitoring amphibian diversity in tropical forests. An evaluation of methods with recommendations for standardization. *Ecotropica.* 10: 1–14.

36. REDD+ Suriname. 2017. REDD+ Nieuws. Edition 1.
37. Schmidt P. 1983. Voortgangsrapport 1978 - 1982 van het project LH/UvS 01 (MABproject 949) “Antropogene ingrepen in het ecosysteem tropisch regenwoud” [Progress report 1978-1982 of the project LH/UvS 01 (MABproject 949) “Anthropogenic disturbance in the tropical forest ecosystem]. CELOS report 136, Paramaribo, Suriname.
38. Schwartz G, Lopes JC, Kanashiro M, Mohren GM, Peña-Claros M. 2014. Disturbance level determines the regeneration of commercial tree species in the eastern Amazon. *Biotropica* 46:148-156. DOI: 10.1111/btp.12096.
39. Shirima DD, Totland Ø, Moe SR. 2016. The relative importance of vertical soil nutrient heterogeneity, and mean and depth-specific soil nutrient availabilities for tree species richness in tropical forests and woodlands. *Oecologia*. 182: 877-888.
40. Silva JNM, Carvalho JOP, Lopes JdoCA, Costa DH, Oliveira LC, Vanclay JK, Skovsgaard JP. 1995. Growth and yield of a tropical rain forest in the Brazilian Amazon 13 years after logging. *For Ecol Manag.* 71: 267-274.
41. Sist P, Fimbel R, Sheil D, Nasi R, Chevallier MH. 2003. Towards sustainable management of mixed dipterocarp forests of South-east Asia: moving beyond minimum diameter cutting limits. *Environ Conserv.* 30: 364-374. DOI:10.1017/S0376892903000389
42. UNIQUE forestry and land use. 2016. Inception report: Background study for REDD+ implementation: Multi-perspective analysis of drivers of deforestation, forest degradation and barriers to REDD+ activities.
43. UN-REDD+ Academy. 2015. Reducing emissions from deforestation and forest degradation. UN-REDD+. edition 1.

44. van Gardingen P, Valle D, Thompson I. 2006. Evaluation of yield regulation options for primary forest in Tapajo's National Forest, Brazil. *For Ecol Manag.* 213: 184-195.
45. van Roosmalen MGM. 1985. Fruits of the Guianan flora. Utrecht: Institute of Systematic Botany.
46. Vidal E, West TAP, Putz FE. 2016. Recovery of biomass and merchantable timber volumes twenty years after conventional and reduced-impact logging in Amazonian Brazil. *For Ecol Manag.* 376: 1-8.
47. Villela DM, Nascimento MT, de Araga LEOC, da Gama DM. 2006. Effect of selective logging on forest structure and nutrient cycling in a seasonally dry Brazilian Atlantic forest. *J Biogeogr.* 33: 506-516.
48. Wegner MJA, editor. 2011. Sustainable Management of Tropical Rainforests: the CELOS Management System. Paramaribo: Tropenbos International.
49. West TAP, Vidal E, Putz FE. 2014. Forest biomass recovery after conventional and reduced-impact logging in Amazonian Brazil. *For Ecol Manag.* 314: 59-63.
doi:10.1016/j.foreco.2013.11.022
50. Zarin DJ, Schulze MD, Vidal E, Lentini M. 2007. Beyond reaping the harvest: Management objectives for timber production in the Brazilian Amazon. *Biol Conserv.* 21 (4): 916-925.
51. Zurita GA, Zuleta GA. 2009. Bird use of logging gaps in a subtropical mountain forest: The influence of habitat structure and resource abundance in the Yungas of Argentina. *For Ecol Manag.* 258: 271-279.
52. Zuur A, Leno EN, Walker N, Saveliev AA, Smith GM. 2009. Mixed effects models and extensions in ecology in R. New York: Springer-Verlag.

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Figures

Figure 1

Figure 2

	RIL	CL	CMS	NAT	p
<i>Forest structure</i>					
Vegetation cover <0.5m	1.7 (SD=0.4)	1.7 (SD=0.3)	1.6 (SD=0.3)	1.6 (SD=0.2)	Ns
Vegetation cover 0.5-3.0m	1.9 (SD=0.5)	1.8 (SD=0.5)	1.7 (SD=0.4)	1.9 (SD=0.5)	Ns
Vegetation cover 3.0-20m	2.7 (SD=0.2)	2.4 (SD=0.1)	1.2 (SD=0.1)	1.7 (SD=0.6)	<0.001
Vegetation cover >20 m	2.3 (SD=0.2)	2.4 (SD=0.1)	1.2 (SD=0.02)	1.6 (SD=0.7)	<0.001
Canopy openness (%)	11.2 (SD=4.7)	12.8 (SD=5.7)	14.9 (SD=7.0)	13.8 (SD=1.2)	<0.001
<i>Vegetation composition</i>					
Shannon index					
vegetation					
SLC	4.1 (SD=0.2)	4.3 (SD=0.1)		4.1 (SD=0.2)	Ns
TES			3.9 (SD=0.1)	4.2 (SD=0.2)	0.04
Simpson index trees	0.9 (SD=0.2)	1.0 (SD=0.01)		0.9 (SD=0.04)	0.02
Simpson index					
vegetation					
SLC	1.0 (SD=0.01)	1.0 (SD=0.0)		1.0 (SD=0.01)	Ns
TES			0.95 (SD=0.01)	0.98 (SD=0.01)	0.02
CWM integrity index					
SLC	0.8 (SD=0.1)	0.8 (SD=0.1)		0.9 (SD=0.02)	Ns
TES			0.8 (SD=0.1)	0.9 (SD=0.02)	0.02
BA commercial trees					
SLC	5.9 (SD=1.3)	5.0 (SD=2.8)		8.5 (SD=2.8)	0.04
TES			11.1 (SD=2.5)	12.3 (SD=4.1)	Ns
BA secondary species					
SLC	2.8 (SD=0.71)	1.8 (SD=0.79)		2.2 (SD=0.7)	Ns
TES			4.2 (SD=2.3)	2.6 (SD=1.3)	Ns

485 **Table 2**

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	1	2	3	4	5	p
<i>Forest structure</i>						
Vegetation cover <0.5 m	1.7 (SD=0.1)	1.7 (SD=0.2)	1.7 (SD=0.1)	1.6 (SD=0.1)	1.6 (SD=0.1)	Ns
Vegetation cover 0.5-3.0m	2.0 (SD=0.2)	1.9 (SD=0.2)	1.8 (SD=0.1)	1.7 (SD=0.1)	1.9 (SD=0.2)	Ns
Vegetation cover 3.0-20 m	2.5 (SD=0.1)	2.7 (SD=0.2)	2.4 (SD=0.1)	1.2 (SD=0.1)	1.7 (SD=0.6)	Ns
Vegetation cover > 20 m	2.2 (SD=0.2)	2.4 (SD=0.1)	2.4 (SD=0.1)	1.2 (SD=0.0)	1.6 (SD=0.7)	Ns
Canopy openness (%)	15.2 (SD=7.0)	8.9 (SD=1.2)	14.3 (SD=6.6)	13.8 (SD=1.2)	12.8 (SD=5.7)	Ns
<i>Vegetation composition</i>						
Shannon diversity index						
SLC	3.9 (SD=0.1)	4.3 (SD=0.1)	4.3 (SD=0.1)		4.1 (SD=0.2)	Ns
TES				3.9 (SD=0.1)	4.2 (SD=0.2)	0.04
Simpson diversity index						
SLC	1.0 (SD=0.01)	1.0 (SD=0.0)	1.0 (SD=0.0)		1.0 (SD=0.01)	Ns
TES				0.954 (SD=0.01)	0.98 (SD=0.01)	0.02
CWM integrity						
SLC	0.09 (SD=0.02)	0.8 (SD=0.03)	0.8 (SD=0.1)		0.8 (SD=0.04)	0.03
TES				0.8 (SD=0.1)	0.9 (SD=0.02)	0.02
BA primary forest trees						
SLC	17.5 (SD=1.3)	14.2 (SD=1.1)	16.6 (SD=5.8)		17.8 (SD=4.8)	0.002
TES				18.4 (SD=0.8)	23.3 (SD=5.8)	Ns
BA secondary forest trees						
SLC	2.3 (SD=0.8)	3.1 (SD=0.7)	2.0 (SD=0.9)		2.0 (SD=0.8)	0.05
TES				4.2	2.6	Ns

Figure Captions

Figure 1. The study areas, Suma Lumber Concession and Tonka experimental site and their position on the Surinamese map. Dots on the Suma Lumber Concession map indicate the study plots, managed according to either reduced impact logging or conventional logging, while the study in the Tonka experimental site was conducted in squares with number 16, 24, 39, and the control plots 41, 42 and 43. These were logged according to the CELOS Management System.

Figure 2. Plot outline. (Young) trees were assessed in 100 x 100 m plots; saplings were assessed in the 5 x 5 m plots; seedlings were assessed in the 2 x 2 m plots. Forest structure assessment was also done in the 2 x 2 m plots.

Figure 3. a. Non-metric multidimensional scaling (NMDS) ordination (Stress=0.065), showing the ordination of plots (CL1-6: Conventional logged plots; NAT1-9: control plots; RIL1-9: Reduced impact logged plots) based on forest structure variables (litter=litter cover, vegetation cover in different strata: vdkl0.5 (vegetation density <0.5m height), vd0.5.3.0 (vegetation density

0.5-3.0m height), vd3.0-20 (vegetation density 3-20m height), vdgr20 (vegetation density >20 m height) and can_fraction (canopy openness)). b. Non-metric multidimensional scaling (NMDS) ordination (Stress=0.14), showing the ordination of plots (RIL plots: RIL1-9, CL plots: CL1-6, NAT plots: NAT1-9, CMS plots: CMS1-3) based on vegetation composition.

Table captions

Table 1. Averages with standard deviation per forest structure (vegetation % cover; litter cover; canopy cover fraction) and vegetation composition (species and functional diversity indices) variables per plot type and the results of the GLMM; SCL: Suma Lumber Concession; TES: Tonka experimental site; Shannon index: Shannon diversity index; Simpson index: Simpson diversity index; BA: Basal area; Ns: non-significant.

Table 2. Averages with standard deviation per forest structure (vegetation % cover; litter cover; canopy cover fraction) and vegetation composition (species and functional diversity indices) variables per age class and the results of the GLMM; SCL: Suma Lumber Concession; TES: Tonka experimental site; Shannon index: Shannon diversity index; Simpson index: Simpson diversity index; BA: Basal area; Ns: non-significant.

531 **Supplementary Material**

532 - Table S1 Averages with standard deviation per forest structure and vegetation composition

533 variables per plot type (all results)

534 - Table S2 Averages with standard deviation per forest structure variable and vegetation

535 composition per age class (all results)

536 - Fig. S1 Boxplots showing the effect of management type on vegetation composition and forest

537 structure variables

538 - Fig S2 Boxplots showing the effect of plot age on vegetation composition and forest structure

539 variables