CERNE

Canopy recovery four years after logging: a management study in a southern brazilian secondary forest

Janine Kervald Likoski[1]✤[iD], Alexander Christian Vibrans[1][iD], Daniel Augusto da Silva[1][iD], Alfredo Celso Fantini[2][iD]

[1] Regional University of Blumenau, Blumenau, Santa Catarina, Brazil

[2] Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil

FOREST ECOLOGY

ABSTRACT

Background: Understanding forest dynamics after logging is essential to define forest management cycles and intensities. In secondary forest, especially in the Atlantic Forest Domain, these studies are still scarce. Monitoring of the canopy structure after tree harvesting can be performed by hemispherical photographs, where canopy opening is commonly analyzed. This study evaluated changes in canopy opening four years after tree harvesting in a secondary Atlantic Rainforest in southern Brazil. We used hemispherical photographs to determine the Canopy Openness (CO), Leaf Area Index (LAI), and Diffuse Fraction of Photosynthetically Active Absorbed Radiation ($FAPAR_{dif}$) in eleven permanent plots.

Results: We found that harvesting resulted in a momentary increase in canopy opening and light availability in the understory. Four years after harvesting, CO, LAI and $FAPAR_{dif}$ recovered or even exceeded the original values of the forest. We observed a significant correlation between CO and number of trees harvested with DBH > 30 cm. Weak correlations were found between these canopy related variables and the logging intensity.

Conclusion: In conclusion, we recognized that changes of CO, LAI and $FAPAR_{dif}$ after timber harvesting presented short duration. This indicates that the applied logging intensities, 21.8 to 51.1% of the total basal area, did not exceed the resilience of the forest canopy and it's recovering four years later. However, additional studies should be carried out to observe vegetation dynamics, such as species composition, vertical structure, productivity and community stability, in order to improve management schemes of secondary stands in the Atlantic Forest.

Keywords: Atlantic Forest, canopy openness, leaf area index, diffuse fraction of photosynthetically active absorbed radiation, sustainable forest management

HIGHLIGHTS

Canopy variables recovered pre-harvesting levels four years after selective logging.
The effects of tree harvesting on the canopy structure seem to be of short term.
Logging intensity apparently does not influence the canopy recovery.
Canopy opening is driven mostly by removal of larger trees (DBH>30 cm).

INTRODUCTION

Secondary forests are frequent or even dominant in many man-modified tropical landscapes (Gardner et al., 2009; Chazdon et al., 2009). About one third of the deforested forests in the Neotropics undergo secondary succession annually (Aide et al., 2013), and most of the global forest cover falls into naturally regenerated forests (74%) (Fao, 2016). These formations are a repository of biodiversity and are responsible for important ecosystem services (Poorter et al., 2016; Melo et al., 2013; Gilroy et al., 2014).

Besides of its increasing extent in the tropics, the management of secondary forests is rarely practiced and only few studies on management systems and rules have been developed in the neotropics (Guariguata; Ostertag, 2001; Fredericksen, 1998). As forest management aims to optimize long-term providing of timber and non-timber products it should be able to guarantee forest maintenance and generate numerous environmental benefits. Brazilian regulations also emphasize in its management definition "cumulative or alternatively, the use of multiple species", in addition to the "use of other goods and services" (Brasil, 2012).

Therefore, management of secondary forests play an essential role in the trade-off between provision of goods and the maintenance of environmental services (Sist et al., 2014). In order to make the best use of available timber resources without harming ecosystem dynamics, it is essential to adopt planning techniques based on mathematical models that allow the prediction of production under the effect of forest interventions (Scolforo, 1998; Schmitz, 2013). However, there is still a superficial understanding of the patterns and factors of forest dynamics after logging, especially in the secondary forests of the Atlantic Coast, where only a few scientific studies and forest management experiments have been developed (Uller et al., 2019; Silva; Vibrans, 2019; Britto, 2017).

In our study areas, Santa Catarina State, 95% of the remaining forests are intermediate or advanced stage secondary stands, covering fragments up to 50 hectares (Vibrans et al., 2019). In these cases, sustainable forest management (SFM) performed by smallholders can reconcile forest resource conservation and income generation (Fantini; Siminski, 2017; Piazza et al., 2017) as an alternative to clear cutting and overexploitation that had negative effects in the past. However currently, smallholders do not benefit from the economic potential of their secondary forests, due to i) lack of technical assistance on silviculture and logging techniques, ii) legal restrictions of natural forest management and the resultant absence of a market for products from natural forests (Fantini et al., 2017; Britto, 2017). Among the economically important species, licurana (Hyeronima alchorneoides Allemão) stands out in the region, a tree that can reach up to 30 m in height and 70 cm in diameter (carvalho, 2008). Its wood has a basic density of 664.5 kg.m-3 (Oliveira et al., 2019) and reaches prices of up to R$ 1,200.00 (around US$ 300,00) per m³ sawnwood in the local market (personal research). As an early secondary species, licurana is abundant in initial stages of succession, in the entire evergreen rainforest in Santa Catarina, sometimes dominating these forests (Siminski et al., 2011).

An important impact generated by timber harvesting is the opening of the forest canopy (Guitet et al., 2012). Several authors have investigated this subject using various methods. One way to monitor canopy structure is by taking hemispherical photographs (HP), focusing the analysis on the Canopy Openness (CO). CO is defined as the portion of the zenith hemisphere not obstructed by the forest canopy (Asner; Keller; Silva, 2004). Its determination using hemispherical photographs unables to infer the quality, quantity and temporal and/or spatial structure of solar radiation penetration (Rich, 1990). Related to CO there are two more metrics that can be obtained from HP: the Leaf Area Index (LAI), which corresponds to the amount of leaf area in a canopy per unit of projected ground surface ($m^2.m^{-2}$) (Chen; Black, 1992), and the direct and diffuse Fraction of Photosynthetically Active Absorbed Radiation (FAPARdir and $FAPAR_{dif}$) (Galvani; Lima, 2014). The latter represents the ability of the vegetation to absorb Photosynthetically Active Radiation (PAR), a fraction of the solar radiation spectrum from 0.4 to 0.7 µm responsible for photosynthesis (Gower; Kucharik; Norman, 1999). CO, LAI as well as FAPAR are important to characterize the canopy and its functions since changes in canopy resulting from management operations result in abiotic and biotic modifications below it; as a result, the microclimate and biological soil properties may be modified that influence the tree species regeneration (Muscolo et al., 2014). Selective logging can alter canopy structure by opening canopies and reducing LAI (Pfeifer et al., 2016). Since LAI and $FAPAR_{dif}$ are inversely correlated with CO, canopy closure recovery will result in higher leaf area and $FAPAR_{dif}$. The gap closure after disturbance or timber harvesting can be monitored over time from repeated samplings in the same area with fisheye lense images (Schleppi; Paquette, 2017).

A comparison between canopy opening estimates at two SFM sites in the Jamari National Forest, in the State of Rondônia, was performed with the LAI-2000 canopy optical analyzer and hemispherical photographs. In such study, more consistent data, with lower standard deviations and lower sensitivity to increased light penetration in the canopy, were obtained with HP (Pinagé et al., 2014). Canopy changes and their effects on regeneration caused by reduced impact logging were investigated in central Amazonia by Darrigo, Venticinque and Santos (2016) using HP. The authors observed that a larger canopy opening persisted until eleven years after logging. This opening supposedly accelerated the growth of trees from species such as Manilkara huberi, Minquartia guianensis, Zygia racemosa and Pouteria anomala in the early years after cutting. The above quoted HP applications have been performed in old growth forest management. As for our knowledge, there are no studies published for secondary forests, which have very different canopy, vertical and horizontal structures than mature forests.

Based on the premise that forests are undergoing complex and continuous ecological changes, including growth, recruitment and mortality, our hypothesis is that CO, LAI and $FAPAR_{dif}$ will recover the values observed before timber harvesting. Therefore, canopy opening is supposed
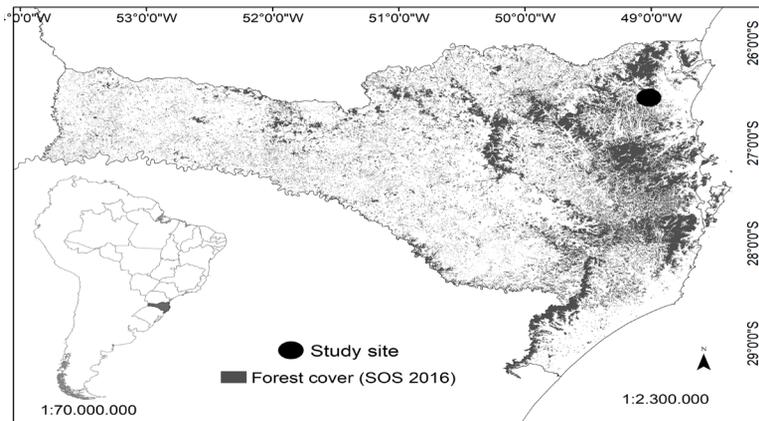
Fig. 1 Study site location in Santa Catarina, Southern Brazil.

to be reversible, allowing the recovery of the forest canopy and understory. The CO tells us about the functional and physiological characteristics of the forest canopy, while LAI and FAPAR are related to ecological processes, such as photosynthesis, evapotranspiration and net primary production. Thus, we can characterize important parts of the canopy structure and its functions, checking if the changes in the canopy, resulting from management operations, have already been overcome four years after the harvest, which tends to normalize the biotic and abiotic processes related to this. Under these points of view, we aimed in this study to investigate if in a secondary forest four years after timber harvesting the canopy structure was reestablished.

MATERIAL AND METHODS

Study area

This study was conducted in a secondary forest located in the northeast of the State of Santa Catarina State, with a total area of 41.9 hectares (26°31′57″S and 49°02′32″O, approximately, Figure 1). The local climate, according to Köppen (Alvares et al., 2013), is classified as Cfa - humid mesothermal without dry season, with annual rainfall ranging from 1.700 mm to 1.900 mm and average temperature of 19 to 20ºC (Pandolfo et al., 2002). The study area presents altitudes between 160 and 500 meters a.s.l., slopes between 30% and 40%, and south-east exposure. The main soil classes are Cambisol and Argisol (Embrapa, 2004).

The forest in the study area was heavily logged until the 1970s to produce sawnwood of the most valuable species. At that time, some forest patches were left amidst of pastures and initial forest regrowth and some remaining trees. An enrichment planting with seedlings of three native species, i.e. *Miconia cinammomifolia* (DC.) Naudin, *H. alchorneoides* and Nectandra spp., was performed in 1978. Irregular spacing was applied and some silvicultural treatments were applied (cleaning and mowing) during the first five years after the plantation.

Experimental design

Eleven 60 x 60 m permanent plots were installed (Figure 2), with 1600 m² of usable area each, divided into 16 subplots of 100m² each. A forest inventory was carried out about six months before harvest, in 2014. In this inventory, we measured the DBH, the total height of all individuals with DBH> 5 cm and the botanical identification was done at the species level, whenever possible. The criteria for the selection of the harvested individuals included mainly their timber quality, their ecological group and abundance at species level (SILVA, 2016). The treatments applied consisted of different harvest intensities, from 21.8 to 51.1% of the total basal area in nine plots (Table 1), in which a total of 695 trees were harvested, mainly *H. alchorneoides*, *M. cinammomifolia*
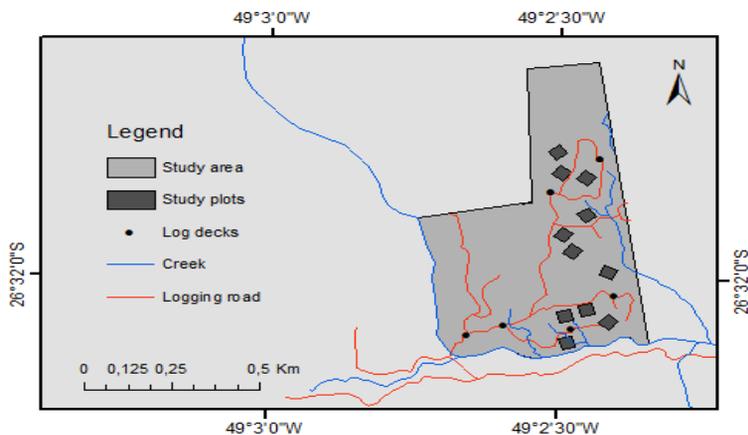
Fig. 2 Study area and plot locations.

Tab. 1 Initial and harvested values of Basal area (G) and tree density (D) per plot.

Plot	G initial (m².ha⁻¹)	Harvested G (m².ha⁻¹)	Harvested G (%)	Initial D (ind·ha⁻¹)	Harvested D (ind·ha⁻¹)	Harvested D (%)
6	29,2	0,0	0,0	1825,0	0,0,0	0,0
20	30,6	0,0	0,0	1575,0	0	0,0
2	34,9	11,4	32,6	2018,8	569,3	28,2
3	33,4	12,5	37,4	1962,5	600,5	30,6
4	24,5	6,8	27,8	1918,8	568,0	29,6
7	37,0	16,4	44,3	2168,8	780,8	36,0
8	31,0	6,9	22,4	1706,3	356,6	20,9
11	31,3	6,8	21,8	1643,8	212,0	12,9
12	30,8	8,6	28,0	1750,0	238,0	13,6
18	43,1	22,0	51,1	1856,3	694,2	37,4
19	25,3	10,3	40,7	1256,3	325,4	25,9
Mean	32,1	9,3	27,8	1789,2	395,0	21,4

and *Nectrandra* spp.. In addition, two control plots were left without treatments.

The canopy structure was initially characterized with zenith hemispherical photographs by Silva e Vibrans (2019), before and right after timber harvesting. New photographs were taken in January 2019 (four years after the forest harvesting intervention), using the same Nikon D3100 model single-lens reflex (DSLR) camera set and 10.5 mm Nikon Fisheye Nikkor lens as in 2014. The camera was positioned at the center of each 10 x 10 m subunit, fixed on a tripod 1.3 m above the ground, with the upper part of the camera facing the magnetic North, according to methodology indicated by Rich (1990). To avoid the effect of sunlight anisotropy and scattering fluxes on the digital image, captures were taken on cloudy days or early in the morning on sunny days (Gonsamo; Pellikka, 2009). The capture of the photographs followed the methodology adapted from Macfarlane et al. (2014) and described by Silva and Vibrans (2019).

Data analysis

Hemispherical photographs were processed using the CAN_EYE software version 6.3.8 (Weiss; Baret, 2017: https://www6.paca.inra.fr/can-eye/), with automatic classification to determine the "vegetation" and "sky" classes, using the ISODATA algorithm (Rildler; Calvard, 1978). The data were then used to calculate CO (expressed in %), LAI (expressed in m².m-²) and FAPAR$_{dif}$ (expressed in %).

Data normality was verified using the Shapiro-Wilk normality test. To verify whether there were significant differences between the mean values observed before as well as immediately and four years after the harvest, a simple variance analysis (ANOVA) was performed with repeated measures, at 5% significance level, followed by Tukey test.

Pearson's linear correlation coefficient was used to verify the relationship between the current CO, LAI and FAPAR$_{dif}$ and i) number and basal area of harvested trees, ii) number and mean diameter of harvested individuals with diameter at breast height (DBH) > 30 cm, iii) number and mean height of trees harvested with a height ≥ 20 m. Because of the very high frequency of H. alchorneoides among the harvested trees, we also estimated the correlation between CO, LAI and FAPAR$_{dif}$ and the DBH and mean height of the harvested trees of this species. All analyzes were performed using the Past 3.25 software (Hammer, 2019: https://folk.uio.no/ohammer/past/).
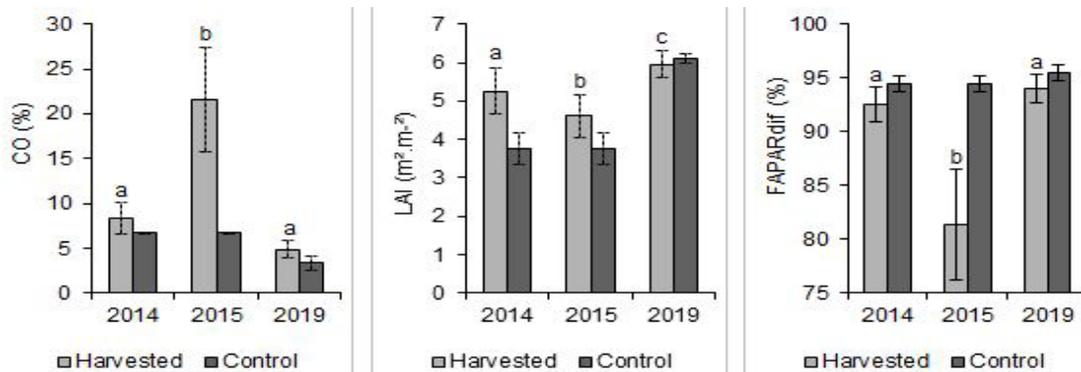
Fig. 3 Canopy opening (CO), leaf area index (IAF) and diffuse fraction of photosynthetically active absorbed radiation (FAPAR$_{dif}$) (means and sd), before, right after and four years after harvest. Different letters indicate a statistical difference among the three measurement periods (α = 0.05).

Tab. 2 Linear correlations (r) between canopy opening (CO), leaf area index (IAF), diffuse fraction of photosynthetically active absorbed radiation (FAPAR$_{dif}$) measured in 2019 and forest structural variables.

Relation	r
CO x G harvested (%)	0,345 ns
CO x n° harvested trees (%)	0,426 ns
CO x n° of trees harvested with DBH > 30 cm	- 0,613 *
CO x $\overline{DBH}$ n° of trees harvested with DBH > 30 cm	- 0,303 ns
CO x n° of trees harvested with a total height ≥ 20 m	- 0,090 ns
CO x Th n° of trees harvested with a total height ≥ 20 m	0,277 ns
LAI x G harvested (%)	0,000 ns
LAI x n° harvested trees (%)	0,086 ns
LAI x n° of trees harvested with DBH > 30 cm	0,261 ns
LAI x $\overline{DBH}$ n° of trees harvested with DBH > 30 cm	0,574 ns
LAI x n° of trees harvested with a total height ≥ 20 m	0,078 ns
LAI x $\overline{Th}$ n° of trees harvested with a total height ≥ 20 m	0,467 ns
FAPAR$_{dif}$ x G harvested (%)	- 0,214 ns
FAPARdif x n° harvested trees (%)	- 0,295 ns
FAPAR$_{dif}$ x n° of trees harvested with DBH > 30 cm	0,535 ns
FAPAR$_{dif}$ x $\overline{DBH}$ n° of trees harvested with DBH > 30 cm	0,460 ns
FAPAR$_{dif}$ x n° of trees harvested with a total height ≥ 20 m	- 0,067 ns
FAPAR$_{dif}$ x $\overline{Th}$ n° of trees harvested with a total height ≥ 20 m	- 0,031 ns
CO x $\overline{DBH}$ Hyeronima alchorneoides harvested	- 0,071 ns
CO x $\overline{Th}$ Hyeronima alchorneoides harvested	0,265 ns
LAI x $\overline{DBH}$ Hyeronima alchorneoides harvested	- 0,470 ns
LAI x Th Hyeronima alchorneoides harvested	- 0,155 ns
FAPAR$_{dif}$ x $\overline{DBH}$ Hyeronima alchorneoides harvested	- 0,094 ns
FAPAR$_{dif}$ x Th Hyeronima alchorneoides harvested	- 0,373 ns

RESULTS

The canopy opening (CO), Leaf area index (LAI) and diffuse fraction of photosynthetically active absorbed radiation (FAPAR$_{dif}$) data presented normal distribution. Harvesting caused the CO to triple compared to 2014 values, a significant increase, but openings were reverted to values statistically similar to the values observed before harvesting. The same pattern was observed to the FAPAR$_{dif}$ values. LAI decreased significantly by harvesting, as expected, but it increased to a value significantly higher than the original one (Figure 3). In general, four years after harvesting the all three canopy variables equalized or even exceeded before harvest levels.

By analyzing the linear correlations between current CO, LAI and FAPAR$_{dif}$ (2019) and harvesting intensity, we found a significant correlation between CO and the number of harvested trees with DBH > 30 cm (Table 2, Figure 4). However, p-values near to the significance limit were observed for the correlation between LAI and FAPAR$_{dif}$ on the one hand and the number of harvested trees with DBH > 30 cm, on the other. This suggests that harvesting of these trees, which implies larger canopy openings, was the factor that most affected the recovery of canopy. We found no significant correlation between CO, LAI and FAPAR$_{dif}$ and the DBH and mean height of the harvested H. alchorneoides trees.

DISCUSSION

In the present study, we found evidence for canopy recovery in a secondary forest four years after logging: CO, LAI and FAPAR$_{dif}$ reached or even exceeded pre-harvesting and control plot levels. We discuss these results mainly against findings from mature forests due to the absence of management studies in secondary forests.

Regarding to LAI, we observed a reduction of its mean values immediately after logging, but higher values than the pre-harvesting ones four years after logging. Our results corroborate the study of Carvalho et al. (2017) who evaluated the impacts of selective logging on canopy openness up to eight years after harvesting, with logging intensity of 11.6, 13.3 and 10.5 m^3·ha^{-1} in each annual production unit, respectively, in the Antimary State Forest (Acre). CO increased due to tree harvesting, but four years later the canopy opening no longer exceeded 10%, showing no significant difference with unlogged areas. The canopy opening is found to be related to the DBH of the felled tree (JACKSON; FREDERICKSEN; MALCOLM, 2002), which in this case, partly explains the lower CO in relation to the cutting intensity applied in our study, since our harvested trees have quite smaller sizes than trees harvested in primary rainforests.

Canopy closure after harvesting can be credited to the growth and architecture of the crowns of the remaining adult individuals and their spatial distribution (Bianchini;
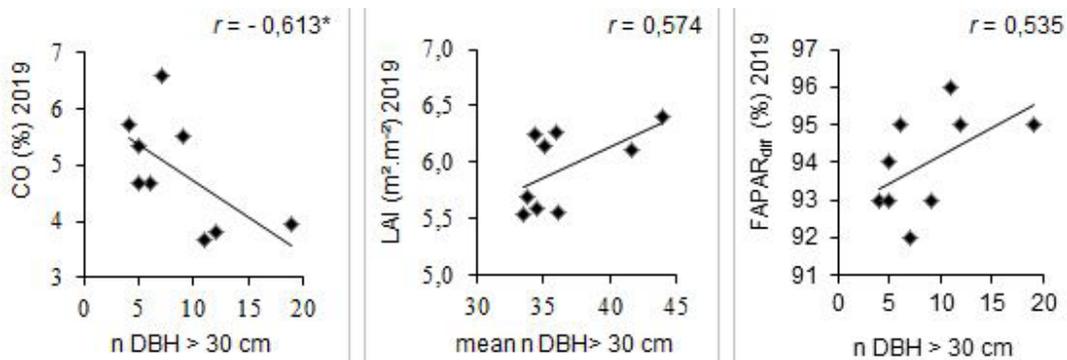
Fig. 4 Relationship between canopy opening (CO), leaf area index (IAF) and diffuse fraction of photosynthetically active absorbed radiation (FAPAR$_{dif}$) and the number of harvested trees (DBH > 30 cm). * indicates a significant Person linear coefficient (p = 0.05).

Pimenta; Santos, 2001). At the same time, the rapid growth of pre-existing seedlings or young trees (Reis et al., 2014) can contribute to the canopy closure. Since our measurements were taken at 1.30 m above ground level, the recovery of the indices was possibly influenced by the regeneration of pioneer species and by the growth of understory species . Indeed, we found that after harvesting the mean height growth of understory species was 1.53 m in 2014, 1.23 m in 2015 and 1.96 m in 2019; pioneer species presented height growth of 1.49 m in 2014, 0.95 m in 2015 and 2.63 m in 2019.The process of canopy closure in control plots (without logging) can be explained by the successional dynamics of the forest, especially by the mean tree heights (8.4 m in 2014 and 10.3 m in 2019).

After logging, the remaining managed forests should pursue their role in providing ecosystem services, such as conservation of species and diversity, forest habitats, stocking wood and CO_2 sinks (Itto, 2016; Yamada, 2016). In the present study, the recovery of CO, LAI and $FAPAR_{dif}$ indicates that the forest, after timber harvesting, seems to keep its multiple functions related to canopy recovery.

Evidences from the literature corroborate this interpretation of our results. Indeed, LAI and $FAPAR_{dif}$ are essential climate variables (Baret et al., 2013) that exert control over water, energy and CO_2 flows (Asner; Scurlock; Hicke, 2003). These are, in turn, determinants of net primary production (NPP) of terrestrial ecosystems (Liu et al., 2018), microclimate (Hardwick et al., 2015) and forest water balance (Silva et al., 2017). Forest canopies create vertical light gradients and minimize the impacts of precipitation and temperature by regulating forest-dependent biodiversity (Nakamura et al., 2017).

Moreover, even in severely damaged forests new leaf cover can darken open canopy areas within a few months (Asner; Keller; Silva, 2004). In proportion to leaf area recovery, photosynthesis and transpiration rates also increase (Miller et al., 2011), which may approach pre-harvest levels within a decade after selective logging (Asner et al., 2010). However, many other functions associated with forests are recovered at different time scales after major disturbances (Trumbore; Brando; Hartmann, 2015), such as species composition and biological diversity. These can regenerate more slowly and take decades to centuries to recover prior to intervention levels (Piponiot et al., 2016).

Thus, in our study the current values of CO, LAI $FAPAR_{dif}$ in general presented low and non-significant correlation coefficients with the different harvesting intensities (from 21.8 to 51.1% of the total basal area, for p = 0.05). This absence of significant correlations indicates that certainly all the different harvest intensities allowed the recovery of forest canopy indices, and that even the highest harvest intensity does not negatively influence or preclude the recovery of the canopy. Likewise, the absence of significant correlations between the canopy indices and the number of harvested trees with total height ≥ 20 m, or with DBH > 30cm, suggests that larger individuals of the Atlantic Forest can be extracted from the forest, without hindering the restoration of CO, LAI and $FAPAR_{dif}$ in a short time (in our case, four years after harvest). The canopy recovery after tree harvesting may be speeded up in secondary forests where species turnover and sucessional dynamic are naturally more intense than in mature forests.

In a previous study in our study area, six months after harvesting, Silva (2016) observed intense colonization by pioneer species, especially Trema micrantha (L.) Blume and Schizolobium parahyba (Vell.) Blake, in the most intensely harvested plots. These species have been replaced afterwards by Myrcia spectabilis DC. and Cecropia glaziovii Snethl. The ingrowth of these species in the understory may explain the (positive) correlation close to the significance level between LAI and $FAPAR_{dif}$ and number e mean diameter of harvested trees with DBH > 30 cm. This latter correlation could also be related to the higher amount of ground-level PAR found in larger and circular clearings than in narrow and irregular openings, as reported by Muscolo et al. (2014). Thus, a larger canopy opening can lead to activation of the seed and/or seedling banks that colonize the understory, reaching four to five meters in height four years after harvesting. As mentioned, the HP taken at 1.30 from the ground can also capture leaf cover of these plants, besides the canopy itself.

Plant productivity or carbon uptake by vegetation is closely related to PAR availability (YANG et al., 2015). In this case, it can be inferred that the vegetation existing in the area four years after forest management, although recovered absorption rates, though is still under succession.

CONCLUSION

This study investigated the recovery of variables related to canopy of a secondary forest after the application of different logging intensities. Changes in CO, LAI and FAPARdif before, right after and four years after harvesting point out to recovery of the canopy. We found merely a weak association between canopy recovery and the different logging intensities. The harvesting had an immediate or short-term impact on the studied canopy related variables. From this perspective, the performed management scheme did not exceed the resilience of the forest canopy. However, we emphasize that additional studies of vegetation dynamics, such as species composition, vertical structure, productivity and community stability, should be carried out to confirm the trends observed here and to improve the management of secondary stands in the Atlantic Forest.

ACKNOWLEDGEMENTS

AUTHORSHIP CONTRIBUTION

Project Idea: JKL, ACV, ACF

Funding: ACV, ACF,

Database: JKL, DAS

Processing: JKL, DAS

Analysis: JKL

Writing: JKL, ACV, ACF

Review: JKL, ACV, ACF

REFERENCES

AIDE, T. Mitchell et al. Deforestation and Reforestation of Latin America and the Caribbean (2001-2010). Biotropica, v. 45, n. 2, p.262-271, 2013.

ALVARES, C. A. et al. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, v. 22, n. 6, p. 711-728, 2013.

ASNER, G. P. et al. High-resolution forest carbon stocks and emissions in the Amazon. Proceedings of The National Academy of Sciences, v. 107, n. 38, p.16738-16742, 2010.

ASNER, G. P.; KELLER, M.; SILVA, J.N. M. Spatial and temporal dynamics of forest canopy gaps following selective logging in the eastern Amazon. Global Change Biology, v. 10, n. 5, p.765-783, 2004.

ASNER, G. P.; SCURLOCK, J. M. O.; HICKE, J. A. Global synthesis of leaf area index observations: implications for ecological and remote sensing studies. Global Ecology and Biogeography, v. 12, n. 3, p.191-205, 2003.

BARET, F. et al. GEOV: LAI and FAPAR$_{DIF}$ essential climate variables and FCOVER global time series capitalizing over existing products. Part1 Principles of development and production. Remote Sensing of Environment, v. 137, p.299-309, 2013.

BIANCHINI, E.; PIMENTA, J. A.; SANTOS, F. A. M. Spatial and temporal variation in the canopy cover in a tropical semi-deciduous forest. Brazilian Archives of Biology and Technology, v. 44, n. 3, p.269-276, 2001.

BRASIL. Lei nº 12651, de 25 de maio de 2012. Dispõe sobre a proteção da vegetação nativa; altera as Leis nos 6.938, de 31 de agosto de 1981, 9.393, de 19 de dezembro de 1996, e 11.428, de 22 de dezembro de 2006; revoga as Leis nos 4.771, de 15 de setembro de 1965, e 7.754, de 14 de abril de 1989, e a Medida Provisória no 2.166-67, de 24 de agosto de 2001; e dá outras providências. Diário Oficial da União, Brasília, section 1, p. 1-11. 2012.

BRITTO, P. C. et al. Productivity assessment of timber harvesting techniques for supporting sustainable forest management of secondary Atlantic Forests in southern Brazil. Annals Of Forest Research, v. 60, n. 2, p.203-2015, 2017.

CARVALHO, A. L. et al. Natural regeneration of trees in selectively logged forest in western Amazonia. Forest Ecology and Management, v. 392, p.36-44, 2017.

CARVALHO, P. E. R. Espécies arbóreas brasileiras. Embrapa Informação Tecnológica, 2008. 593 p.

CHAZDON, R. L. et al. Beyond Reserves: A Research Agenda for Conserving Biodiversity in Human-modified Tropical Landscapes. Biotropica, v. 41, n. 2, p.142-153, 2009.

CHEN, J. M.; BLACK, T. A. Foliage area and architecture of plant canopies from sunfleck size distributions. Agricultural and Forest Meteorology, v. 60, n. 3-4, p.249-266, 1992.

DARRIGO, M. R.; VENTICINQUE, E. M.; SANTOS, F. A. M. Effects of reduced impact logging on the forest regeneration in the central Amazonia. Forest Ecology and Management, v. 360, p.52-59, 2016.

EMBRAPA. Solos do Estado de Santa Catarina. Embrapa, 2004. 745 p.

FANTINI, A. C. et al. The demise of swidden-fallow agriculture in an Atlantic Rainforest region: Implications for farmers' livelihood and conservation. Land Use Policy, v. 69, p.417-426, 2017.

FANTINI, A. C.; SIMINSKI, A. Manejo de florestas secundárias da Mata Atlântica para produção de madeira: possível e desejável. Revista Brasileira de Pós-graduação, v. 13, n. 32, p.673-698, 2017.

FAO. Global Forest Resources Assessment 2015: How are the world's forests changing?. Roma: Food and Agriculture Organization Of The United Nations, 2016. 54 p.

FREDERICKSEN, T. S. Limitations of Low-Intensity Selection and Selective Logging for Sustainable Tropical Forestry. The Commonwealth Forestry Review, v. 77, n. 4, pp. 262-266, 1998.

GALVANI, E.; LIMA, N. G. B. Fotografias hemisféricas em estudos microclimáticos: Referencial teórico-conceitual e aplicações. Ciência e Natura, v. 36, n. 3, p.215-221, 2014.

GARDNER, T. A. et al. Prospects for tropical forest biodiversity in a human-modified world. Ecology Letters, v. 12, n. 6, p.561-582, 2009.

GILROY, J. J. et al. Cheap carbon and biodiversity co-benefits from forest regeneration in a hotspot of endemism. Nature Climate Change, v. 4, n. 6, p.503-507, 2014.

GONSAMO, A.; PELLIKKA, P. A new look at top-of-canopy gap fraction measurements from high-resolution airborne imagery. Earsel Eproceedings, v. 8, n. 1, p.64-74, 2009.

GOWER, S. T.; KUCHARIK, C. J.; NORMAN, J. M. Direct and Indirect Estimation of Leaf Area Index, FAPAR$_{dif}$ and Net Primary Production of Terrestrial Ecosystems. Remote Sensing of Environment, v. 70, n. 1, p.29-51, 1999.

GUARIGUATA, M. R.; OSTERTAG, R. Neotropical secondary forest succession: changes in structural and functional characteristics. Forest Ecology And Management, v. 148, n. 1-3, p.185-206, 2001.

GUITET, S. et al. Impacts of logging on the canopy and the consequences for forest management in French Guiana. Forest Ecology and Management, v. 277, p.124-131, 2012.

HAMMER, Øyvind. PAST: PAleontological STatistics. Natural History Museum, University Of Oslo, 2019. 275 p.

HARDWICK, S. R. et al. The relationship between leaf area index and microclimate in tropical forest and oil palm plantation: Forest disturbance drives changes in microclimate. Agricultural and Forest Meteorology, v. 201, p.187-195, 2015.

ITTO. Criteria and indicators for the sustainable. International Tropical Timber Organization, 2016. 82 p.

JACKSON, S. M; FREDERICKSEN, T. S.; MALCOLM, J. R. Area disturbed and residual stand damage following logging in a Bolivian tropical forest. Forest Ecology and Management, v. 166, n. 1-3, p.271-283, 2002.

LIU, L. et al. Broad Consistency Between Satellite and Vegetation Model Estimates of Net Primary Productivity Across Global and Regional Scales. Journal of Geophysical Research: Biogeosciences, v. 123, n. 12, p.3603-3616, 2018.

MACFARLANE, C. et al. Digital canopy photography: Exposed and in the raw. Agricultural and Forest Meteorology, v. 197, p.244-253, 2014.

MELO, F. P. L. et al. On the hope for biodiversity-friendly tropical landscapes. Trends in Ecology & Evolution, v. 28, n. 8, p.462-468, 2013.

MILLER, S. D. et al. Reduced impact logging minimally alters tropical rainforest carbon and energy exchange. Proceedings of The National Academy of Sciences, v. 108, n. 48, p.19431-19435, 2011.

MUSCOLO, A. et al. A review of the roles of forest canopy gaps. Journal of Forestry Research, v. 25, n. 4, p.725-736, 2014.

NAKAMURA, A. et al. Forests and Their Canopies: Achievements and Horizons in Canopy Science. Trends in Ecology & Evolution, v. 32, n. 6, p.438-451, 2017.

OLIVEIRA, L. Z. et al. Towards the Fulfillment of a Knowledge Gap: Wood Densities for Species of the Subtropical Atlantic Forest. Data, v. 4, n. 3, p.104-113, 2019.

PANDOLFO, C. et al. Atlas climatológico do Estado de Santa Catarina. Epagri, 2002. CD-ROM.

PFEIFER, M. et al. Mapping the structure of Borneo's tropical forests across a degradation gradient. Remote Sensing of Environment, v. 176, p.84-97, 2016.

PIAZZA, G. E. et al. Regeneração natural de espécies madeireiras na floresta secundária da Mata Atlântica. Advances in Forestry Science, v. 4, n. 2, p.99-105, 2017.

PINAGÉ, E. R. et al. Gap Fraction Estimates over Selectively Logged Forests in Western Amazon. Natural Resources, v. 05, n. 16, p.969-980, 2014.

PIPONIOT, C. et al. Carbon recovery dynamics following disturbance by selective logging in Amazonian forests. Elife, v. 5, p.1-19, 2016.

POORTER, L. et al. Biomass resilience of Neotropical secondary forests. Nature, v. 530, n. 7589, p.211-214, 2016.

REIS, L. P. et al. Crescimento de mudas de Parkia gigantocarpa Ducke, em um sistema de enriquecimento em clareiras após a colheita de madeira. Ciência Florestal, v. 24, n. 2, p.431-436, 2014.

RICH, P. M. Characterizing Plant Canopies with Hemispherical Photographs. Remote Sensing Reviews, v. 5, n. 1, p.13-29, 1990.

RIDLER, T. W.; CALVARD, S. Picture Thresholding Using an Iterative Selection Method. IEEE Transactions on Systems, Man, and Cybernetics, v. 8, n. 8, p.630-632, 1978.

SCHLEPPI, P.; PAQUETTE, A. Solar Radiation in Forests: Theory for Hemispherical Photography. In: FOURNIER, R. A.; HALL, R. J. Hemispherical Photography in Forest Science: Theory, Methods, Applications. Springer, 2017. p. 15-52.

SCHMITZ, H. M. Produção de madeira em florestas secundárias de Santa Catarina: ecologicamente viável e socialmente desejável. 2013. 114 p. Masters dissertation. Universidade Federal de Santa Catarina, Florianópolis.

SCOLFORO, J. R. S. Manejo florestal. UFLA/FAEPE, 1998. 438 p.

SILVA, B. et al. Area-wide evapotranspiration monitoring at the crown level of a tropical mountain rain forest. Remote Sensing of Environment, v. 194, p.219-229, 2017.

SILVA, D. A. Efeito da intensidade de colheita sobre a estrutura remanescente de uma floresta secundária manejada em Guaramirim – SC. 2016. 85 p. Masters dissertation. Universidade Regional de Blumenau, Blumenau.

SILVA, D. A.; VIBRANS, A. C. Canopy Architecture After Selective Logging in a Secondary Atlantic Rainforest in Brazil. Floresta e Ambiente, v. 26, n. 4, p.1-10, 2019.

SIMINSKI, A. et al. Secondary Forest Succession in the Mata Atlantica, Brazil: Floristic and Phytosociological Trends. Isrn Ecology, v. 2011, p.1-19, 2011.

SIST, P. et al. The Tropical managed Forests Observatory: a research network addressing the future of tropical logged forests. Applied Vegetation Science, v. 18, n. 1, p.171-174, 2014.

TRUMBORE, S.; BRANDO, P.; HARTMANN, H. Forest health and global change. Science, v. 349, n. 6250, p.814-818, 2015.

ULLER, H. F. et al. Aboveground biomass quantification and tree-level prediction models for the Brazilian subtropical Atlantic Forest. Southern Forests: a Journal of Forest Science, v. 81, n. 3, p.261-271, 2019.

VIBRANS, A. C.et al. Insights from a large-scale inventory in the southern Brazilian Atlantic Forest. Scientia Agricola, v. 77, n. 1, p.1-12, 2019.

WEISS, M.; BARET, F. CAN_EYE V6.4.91 User Manual. UMT CAPTE / UMR1114 EMMAH, INRA, 2017. 56 p.

YAMADA, T. Long-term effects of selective logging on tropical forest ecosystems: a case study of the Pasoh Forest Reserve. Japanese Journal of Ecology, v. 66, n. 2, p.275-282, 2016.

YANG, X. et al. Solar-induced chlorophyll fluorescence that correlates with canopy photosynthesis on diurnal and seasonal scales in a temperate deciduous forest. Geophysical Research Letters, v. 42, n. 8, p.2977-2987, 2015.