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Full Research Article

Regeneration of Commercial Tree Species and Long Term Compositional and Structural Changes in a Logged and Silviculturally Treated Brazilian Rainforest, 1955-1993

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Abstract

The study presented here consisted of an extensive literature investigation on the long term silvicultural experiments of Curua Una research station in the state of Para, Brazil. The objective of the work was to assess the long term ecological and financial sustainability of a set of silvicultural treatments by using numerical figures derived from the literature related to the financial and ecological impacts of the different treatments in the scale of calendar decades. There were 5 treatments including undisturbed forest (control). The remaining four where in two categories. The first included measures to increase natural regeneration of commercial species prior to exploitation. The second included measures aimed at increasing stocking of commercials after exploitation. Adequate data was found to assess the short term success rate of all 5 treatments in terms of achieving adequate stocking of commercial tree species in sizes of trees $\leq$5 cm dbh in the first few years after initiation. It was also possible to assess tree species community composition, structure and timber financial value for trees $\geq$5 cm dbh for a period of 15 years following initial treatment for one and for 36 years after initial treatment for two others. The measures used where the stocking index (S.I.) and the establishment factor (E.F.) for the early results and the Shannon-Weinner species diversity index, total % volume of commercial tree species (TPCTV), total volume of potentially commercial tree species (TPTV), harvestable volume in the year 1993 (HV), number of stems ha^{-1} (STD) and stand basal area in m^2 ha^{-1}. Results showed that overall silvicultural systems that included post exploitation treatments where generally more sustainable in terms of long term biodiversity value and more financially profitable relative to systems which relied on post exploitation treatments. These results suggest that drastic revision of current legislation must take place in nations with Amazonian forest because these currently include only post exploitation silvicultural treatments.

1. Introduction

The native tropical and subtropical rainforests of South America represent the largest intact tropical forest resource worldwide (FAO, 2013). However they are facing increasing levels of anthropogenic disturbance and loss of area as a result of competition with other land uses mostly agriculture (soya and cattle) and commercial timber tree plantations (Morton et al., 2006).The conservation of these forests is considered of prime worldwide concern for a variety of reasons mostly related to biodiversity conservation and protection against climate change (Constanza et al., 1997, Grenyer et al., 2006, Kier et al., 2005). Despite this they are disappearing at an ever increasing rate (Rojas-Briales and Ze Meka, 2011) with remaining forest also badly ecologically affected at a rate many times multiple of this (Asner et al., 2006). Unsustainable logging has been recognized as a main catalyst for the loss of native forest to other land uses through the opening of roads with the co-occurring degradation of the resource (Asner et al., 2006). These issues only serve to aggravate the challenge of conserving it due to the unprofitability of the impaired ecosystem that in many cases requires large input of capital to go to restoration of the ecosystem using techniques that are most often experimental or scientifically questionable (Rodrigues et al., 2009). Despite these problems the potential of sustainable forms of timber harvesting especially in the general context of a holistic low impact sustainable forest management has long been recognized as a major potential driver of sustainable development for the region and as a barrier to degradation and deforestation(Reyer, 2009). It is however

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vital that for a sustained second and subsequent harvests to be insured adequate regeneration of commercial tree species be achieved as well as adequate growth of stems in the residual stand. The main challenge so far in most instances is the apparent lack of adequate advance regeneration of commercial tree species following predatory (unsustainable) and in some instances sustainable logging practices (Kukkonen et al., 2008; Schwartz et al., 2013). This problem is potentially underestimated however due to the exclusion of regeneration monitoring of commercial tree species as factors in management plans (Kukkonen et al., 2008) which is what happens in the majority of situations in the Brazilian Amazon due to the current exclusion of this in relevant legislation (personal observation). An important question with respect to this is how can the sylvigenetic cycle be tracked and manipulated in order that both ecological and narrow sense timber yield sustainability is achieved as part of the forest management plan. In this paper results on long term regeneration dynamics, forest structure and composition are presented from the longest running silivicultural field experiment in tropical South America. Experiments where established in previously undisturbed semi deciduous terrafirme (non-flooded forest) in 1955 in the now in operational Curua Una Silvicultural research station in the state of Para, Brazil. The trials included using primary forest as a control to study the impact of various kinds of silvicultural treatments in terms of long term timber production potential, forest structure and composition and effects on soil properties. Here information was collated from a variety of published official sources to track the progress of these experiments with the aim of drawing conclusions with respect to wood production and land management plans for the region in the context of sustainable development. The hypothesis is that native forest management systems based on manipulation and monitoring of natural regeneration and especially pre-exploitation silvicultural treatments aimed at stimulating adequate regeneration of commercial species are ecologically more sustainable relative to ones with post exploitation treatments such as enrichment planting and prove that regeneration of commercial tree species and composition are essential factors to consider when assessing the impact of selective logging.

2. Materials and Methods

2.1. Study site

The Curua Una forest reserve and the experimental station that lies within its borders are at the confluence of the Amazon and Curua-Una rivers in the state of Para´, Brazil (Figure 1). (02°38´S 54°57´W) 110 km east of Santarem. The life zone in this region is classified as tropical moist forest. Most terra firme forest at the reserve is on the planalto, which is a plateau that rises to 180 masl approximately 6 km from the Curua Una River. The native forest of the experimental site has both deciduous and broadleaf trees in the overstory. Main commercial tree species present in the site itself include *Jacaranda Copaia, Didymopanax morotoni, Goupia glabra* and *Manilkara huberi* while canopy dominants are species like *Didymopanax morotoni* and *Vochysia maxima*. In this forest, there are approximately 103-140 tree species ha^{-1} (≥10 cm dbh). Leguminosae, sapotaceae, lechythidaceae and laureaceae are the taxonomic families most frequently represented. Average yearly rainfall at the station is 1900 mm, most of which falls from December to July, and the average daily temperature is 26 ^{o}C (Sudam, 1979). Soils on the plateau are Oxisols (Typic Haplustox), and surface soils (0-20 cm depth) have clay contents of 60%, a pH of 4.5, and an ECEC of 1.6 cmol$_c$ kg^{-1} (Smith et al., 1998a).

2.2. Experiments

2.2.1. Control treatment (CT-total size of experimental area 100 ha)

A 100 ha area of forest was selected based on proximity and edaphological and ecological conditions similar to the treatment areas adjacent to it. The area was selected in 1993 as part of the comparative study of Yared (1995).

2.2.2. Brazilian tropical shelterwood system (BTSS-total size of experimental area 6.25 ha)

A modified version of the tropical shelterwood system originally developed for African rainforest. Treatments started in 1957 with selective poisoning in first years and periodic monitoring and if regeneration of commercial tree species is found sufficient exploitation of a minimum of 60% of total harvestable commercial tree volume takes place. Intermediate thinnings start and continue until next 60-80 year rotation

Figure 1: Location of the study area

including tending and cleaning to promote the regeneration desirable stems considering trees ≥5 cm dbh for elimination. For more details on the operational plan for this experiment Yared (1995) provides an excellent review.

2.2.3. Regeneration group felling system (RGFS-total size of experimental area 6.25 ha)

In 1957, light cutting of the underwood (3-4 man days ha^{-1}) and 25 uneconomics ha^{-1} where poisoned. This was followed by group fellings worked out with a view to open evenly distributed gaps each with a diameter approximately equal to the ecodominant height of the original stand leaving single rows of trees of the ecodominant canopy between the gaps. Within the gaps commercials were felled and removedand non-commercials burned. Residual crowns and branches are in series sliced and redistributed. This final measure was primarily aimed at clearing the ground to create conditions favorable to natural regeneration of tree species. Pitt (1961) provides more details on this.

2.2.4. Post exploitation tropical shelterwood system (TSS-total size of experimental area 10 ha)

A silvicultural system that was first applied on an experimental basis for this site starting in 1957. Following commercial exploitation at intensity of 50-60 m^3 ha^{-1}, cutting non-commercial saplings taller than 4 m except economics. Planting of economics was done in some of the area in mixtures, at a rate of 650 seedlings ha^{-1}. Another area was enriched only with *Cedrela odorata*. Intermediate poisoning treatments to stimulate growth and regeneration of commercials like in TSS continued. Pitt (1961) provides more details on this.

2.2.5. Methode okoume adapted for quaruba (MOAQ-total size of experimental area 6.6 ha)

Essentially a method used in Africa with *Aucomea* sp adapted here for *Vochysia Maxima*. Following complete removal of all commercial trees in the first year (1978) of harvestable volume the complete clearing of small patches within the natural forest with bulldozers and chemicals followed and after that planting of the desired species (*Vochysia maxima*). In the third year an additional 30% relative to the original amount of *Vochysia maxima* where planted. Maintenance of the area followed after this consisting of assisting the planted trees and all other naturally regenerating commercials by liberation from vines and clearing around the desired trees considering commercial trees ≥5 cm dbh. These treatments continued until 2 years before the surveys where done by Yared (1995) in 1993.

2.3. Assessment of early forest response to silvicultural treatments

The measures used by the FAO mission to the Amazon (Pitt, 1961; Dubois, 1971) to track early stand condition and development for native forest where the stocking index (equation 1) and the establishment factor (equation 2) . These where calculated considering what tree species where commercial in terms of having a value in the timber market at the time the measurements where done

$$\text{Stocking index(S.I.)=}\sum \frac{\frac{R}{100}+\frac{U}{10}+E+S}{N_t}\times 100 \quad (1)$$

Where R=recruits (less than 20 cm high), U=unestablished (from 0.2 to 2 m high), E=established (more than 2 m high and less than 5 cm dbh), NT=total number of quadrats surveyed

$$\text{Establishment factor (E.S.F)=}\frac{N_s}{N_t}\times\frac{H_t}{H_e}\times 100 \ (2)$$

Where N_s=Number of stocked quadrats, N_t=total number of quadrats,H_t=average height of tallest in each quadrat, H_e=Establishment height (2 m). It is worth noting that for purposes of data analysis all plants over the fixed establishment height where treated as only equivalent of it.

2.2.4. Commercial timber value of forest

Data was available from Yared (1995) for the year 1993 for the for the end of the 36 year period for the Control (CT) undisturbed forest treatment and the Brazilian tropical shelterwood system (BTSS) and the Methode Okume adapted for Quaruba (MOAQ) for the end of a 15 year period following treatment of originally undisturbed forest. Data was available for three variables. These where total % of volume in m^3 of all trees of commercial species considering all trees ≥5 cm dbh in the survey area=% TCTV, total % of volume in m^3 of all trees of potentially commercial species considering all trees ≥5 cm dbh in the survey area=% TPCTV and Harvestable volume per hectare of commercial tree species in the year 1993 (m^3 ha^{-1} considering trees dbh ≥45 cm dbh)=HV.

2.2.5. Biodiversity value

It was possible to estimate indirectly the biodiversity value of the forest of some of the treatments using the data of Yared (1995) for the end of the 36 year period for the Control (CT) undisturbed forest treatment and the Brazilian tropical shelterwood system (BTSS) and the Methode Okume adapted for Quaruba (MOAQ) for the end of a 15 year period following treatment of originally undisturbed forest. This was done for tree species diversity and structural diversity the two fundamental measures of community diversity that are also indirect predictors of important issues like value for wild fauna. Tree species diversity between the treatments was assessed by comparing values for the Shannon-Weinner diversity index along with their respective statistics (Coefficient of variation, variance of the mean, maximum, minimum and mean) for trees ≥5 cm dbh. As trees are the physiognomic dominant of the community this they define along with structural diversity the biological diversity of a site relative to another. This is described by equation 3.

$$H=\sum_{i=1}^{S} p_i \ln p_i \quad (3)$$

Where H: Shannon-Weinner index, N: total number of individuals sampled, n_i: number of individuals sampled for the i-th species, S: number of species sampled, ln: neperian logarithm and $p_i=n_i/N$. As measures of structural diversity the stand basal area in m^2 ha^{-1} and number of stems $\geq$5 cm dbh ha^{-1} where used to explore potential differences.

3. Results and Discussion

3.1. Early response to silvicultural treatments

Values for the analyzed variables were significantly different across the treatments following application of the first set of prescribed measures (Table 1). It is clear that the Brazilian tropical shelterwood system (BTSS) was the most successful in achieving natural regeneration of commercial tree species and better performance of these overall but only marginally so in relation to the regeneration (RGFS) group fellings system. However due to the deliberate planting at high densities of *Vochysia maxima* in the MOAQ system this ranked first in relation to all other systems with finally the PEXTSS system ranking last in relation to all of them with a significant difference. This was true for both the stocking index and the establishment factor meaning that there were not simply more trees of the desired species in these size classes but were also growing and performing faster overall. A pattern of correlation between stocking index and establishment factor was noted with levels being proportional throughout the treatments. This is latter pattern is a logical one as better conditions for establishment are most likely to be correlated with better subsequent survival and early growth of trees for all species. These results are in agreement for similar practices like the PEXTSS where initial logging of most or some of the harvestable stems takes place from the Honduras (Kukkonen and Hohwald, 2009) and the Maya forest (Nesheim and Halvorsen, 2011) suggesting the unsustainability of such practices in these forests based on these finds. However, as stocking guides and dynamic models that incorporate regeneration as a factor are either nonexistent or in the early stages of development such as the example of van Ulft (2004) such conclusions would require more long term data. It should also be noted that the number of commercial tree species has changed significantly since the period these measurements were taken in the Brazilian Amazon as increasing number of tree species have become marketable and are therefore harvested for timber (Ahmed and Ewers, 2012). This would mean that had the measurement taken place now the results may have potentially been different. How different unfortunately cannot be known as no suitable data is available from that time and experiments cannot be repeated as the station is in operational to derive values for these. Ideally however, the evolution of such treatments is followed over time to the point of the end of a complete harvesting cycle as initial conditions don’t always correlate perfectly with later stand development.

3.4. Long term effects

It is clear that there was a significant difference in all the variables for all the silvicultural treatments following the set of prescribed measures of a stand over a 36 year time period for the BTSS system and MOAQ for a 15 year respectively in relation to the control treatment or undisturbed forest (Table 2). The treatments reduced the Shannon-Weinner index (SWI) significantly and hence tree species diversity considering stems ≥5 cm dbh in relation to the undisturbed forest. More specifically differences where smaller for the BTSS system in relation to the MOAQ. This pattern can be expected for three reasons. The first is that the treatments where more radical (involving extensive tree cutting and planting and tending) in relation to the BTSS, and the second that the experiment was at a much earlier stage (15 vs.36 years). The third and most important reason is that because current theory suggests that the primary forest is the climax undisturbed forest community and with increasing disturbance there is increasing regression to more earlier stages of ecological succession and hence decreased species richness as a direct consequence of this. This

Table 1: Early results of regeneration stocking of commercial tree species

Silvicultural treatment	Stocking index (S.I)	Establishment factor (E.F.)	Date	Source
CT (control)	<50%	<50%	1958	Inferred[*]
BTSS	98.3%	91%	1958	Dubois (1971)
MOAQ	≥100%	≥100%	1978	Inferred[**]
PEXBTSS	72%	60%	1958	Pit (1961)
RGFS	83.4%	87.8%	1966	Dubois (1971)

CT: Control treatment-undisturbed forest); BTSS: Brazilian tropical shelterwood system; MOAQ: Methode Okume adapted for *Vochysia maxima*; [*]Inferered from values of linear regeneration surveys in Pitt (1961) and Dubois (1971); [**]Individuals of Vochysia Maxima where planted in lines leading to perfect stocking of commercials

Table 2: Long term ecological and financial effects of selected silvicultural treatments

Treatment	%TCTV	%TPCTV	HV (m^3 ha^{-1})	SWI	STD (stems ha^{-1})	STBA (m^2 ha^{-1})	First treatment (year)	Source
CT (control)	40	45	30	2.82	996	29.4	None	Yared 1995
BTSS	78	35	29.9	2.53	815	33.5	1964	Yared 1995
MOAQ	39	28	0	2.29	1204	21	1978	Yared 1995

CT: Control treatment-undisturbed forest); BTSS: Brazilian tropical shelterwood system; MOAQ: Methode Okume adapted for *Vochysia maxima*; % TCTV: Total % of volume in m^3 of all trees of commercial species considering all trees $\geq$5 cm dbh in the survey area; % TPCTV: Total % of volume in m^3 of all trees of potentially commercial species considering all trees $\geq$ 5 cm dbh in the survey area; HV: Harvestable volume of commercial tree species in the year 1993 (m^3 ha^{-1} considering trees dbh $\geq$45 cm dbh); SWI: Shannon-Weinner species diversity index considering stems of all tree species $\geq$5 cm dbh; STBA: Stand basal area (m^2 ha^{-1}) considering stems $\geq$5 cm dbh; STD: Stan stem density considering stems $\geq$5 cm dbh (stems ha^{-1})

hypothesis is further supported by the structure of the stands which shows also a pattern of increasing disparity with the primary forest with decreasing stand basal area (STBA) and increasing stem density (STD). Results here for the BTSS for composition and structure in relation to undisturbed forest are somehow similar to the ones reported by Asante-Yeboa (2011) for the Bobiri forest reserve in Ghana, West Africa (treated in 1945 and surveyed in 2008 viz. 1959 and 1993 respectively for Curua Una) as far as the Shannon-Weinner diversity index is concerned for trees $\geq$5 cm dbh. This result can be partly expected as this was essentially a modification of the African tropical shelterwood system. This also suggests that the effects may be equally long lasting for Amazonian forest and suggests common functional community responses to this form of disturbance. Despite differences in the stage of treatment in 1993 between the BTSS and MOAQ treatment it is apparent that the differences in stand composition and structure are far more within acceptable limits for purposes of biodiversity conservation if one considers that the undisturbed forest is the one with the maximum biodiversity value considering the most recent analyses of Gibson et al. (2011). There were also significant differences between the treatments in terms of total commercial tree volume of trees $\geq$5 cm dbh (% TCTV), % total volume of potentially commercial tree species $\geq$5 cm dbh (TPCTV) and harvestable volume of commercial tree species in the year 1993 considering only trees $\geq$45 cm dbh (HV). More specifically there was a gradient of increasing volume with the BTSS ranking first followed by Control or undisturbed forest and finally MOAQ. The BTSS treatment had achieved at increasing the amounts of commercial tree species in relation to the undisturbed forest but at the slight but significant expense of potentially commercial tree species in relation to the undisturbed forest. This may have important implications as more species become marketable in the near or distant future and hence long term financial gain may be compromised to an extent in relation to other treatments that could potentially have been applied (Ahmed and Ewers, 2012). Despite this drawback the BTSS still managed to recover HV in relation to the undisturbed forest within a 36 year time period and increase the proportion of commercials in the forest which may lead to a second greater economic harvest over a time period of 36 years. The MOAQ treatment despite being 15 years old and with all the care of opening the enrichment lines and tending the trees with the fast growing early successional tree species *Vochysia maxima* there was still no harvestable volume gained during this period. This has important implications for sustainable forest management as currently practiced in many working forests in Brazilian Amazonia but also elsewhere with plans that dictate that enrichment planting should follow right after the selective logging treatment without any previous measurement of regeneration required or attempts to stimulate it in the case it is unsuccessful (Sabogal et al., 2006) as was the case with the mentality behind some of the experiments (MOAQ, PEXTSS) examined in this study.

4. Conclusion

Pre-exploitation treatments are essential for sustainable forest management in these forests as stocking of commercials in the classes relevant to regeneration is too low to allow for a second satisfactory harvest at the level of management envisaged. Funds currently used for producing and planting juvenile trees in enrichment lines following logging should be concentrated at achieving natural regeneration prior to first logging. Funds from schemes like REDD (reducing dioxide emissions from deforestation) can also be used potentially. Before anything, however, such measures and guidelines need to be properly incorporated into legislation and for this more research is needed especially with respect to trees $\leq$10 cm dbh. These results lead us to maintain the null hypothesis that silvicultural systems focused on achieving natural regeneration prior to harvest are more sustainable in relation to ones that focus on pre-exploitation treatments and enrichment planting.

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