Dynamics of natural tropical forest after selective timber harvesting in Papua New Guinea

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Abstract

The dynamics of forest after timber harvesting is a major issue for tropical forest managers and communities. Timber harvesting provides income to communities and governments and resources to industry but it has also been identified as a potential contributor to deforestation and degradation of tropical forests. The contribution of harvesting to greenhouse gas emissions has recently become the focus of international mitigation efforts such as reducing emissions from deforestation and forest degradation. In Papua New Guinea (PNG), harvesting is primarily occurring in accessible primary forests but the fate of these forests under current harvesting practices is uncertain.

In this study, we investigate the impacts of selective timber harvesting on stand structure, growth and dynamics, recovery and degradation, and species diversity; and impacts of the 1997-1998 El Nino induced forest fire on basal area (BA) growth and mortality rates of the natural tropical forests in PNG using data from 110, one hectare permanent sample plots distributed across the country and measured for over 15 years by the PNG Forest Research Institute (PNGFRI). We analysed 98 of these plots to examine temporal trends in BA after selective-harvesting while 21 of the plots that were burnt during the 1997-1998 El Nino drought were analysed to assess their mortality rates. We tested a model developed in Queensland tropical forests to determine whether or not a critical threshold BA exists for the recovery of harvested tropical forests in PNG. Results from logarithmic regression analysis of the relationship between starting BA (STBA) and stand BA increment (SBAI) after selective timber harvesting showed a positive increase in BA growth ($r^2 = 0.75$, $p<0.05$) however, a single critical threshold BA does not exist that determines whether a harvested forest degrades or recovers. Our analysis suggests that, the response to harvesting is variable, with the majority of plots (76%) showing an increase in BA and remainder a decrease.

We found that BA of selectively-harvested tropical forests in PNG is about 18m^2 ha^{-1} ± 0.45, which is a reduction of about 40% from the initial stand of intact primary forest. Average annual increment in BA across all plots was 0.18 m^2 ha^{-1} yr^{-1} ± 0.61 however, analysis indicated that, BA is affected by high mortality rates on plots severely burnt during the El Nino fires. Thus, these forests generally show capacity to recover after selective timber harvesting, even when the residual basal area is low. The future fate of these forests will depend on the degree of future harvesting, potential conversion to agriculture and the impact of fire and other disturbances.

Key words: Basal area, El Nino, mortality, permanent sample plot, species diversity, Shannon-Wiener Index.

1. Introduction

Tropical forests are subject to extensive human disturbance such as clearance for agriculture, infrastructure development, fires and mining. There has been considerable debate about timber harvesting in tropical forests and its impacts on environmental, cultural and social values. The implementation of sustainable forest management in tropical forests is a widespread goal of the international community but, while there is some evidence of improvement, few forest areas are currently considered to be managed sustainably (ITTO, 2006). More recently, international attention on implementation of sustainable forest management (SFM) has increased as a result of the focus on greenhouse gas emissions associated with deforestation and forest degradation in the tropics and the potential to reduce emissions from these sources as a low cost climate change mitigation option UNFCCC (2006; 2009).

In Papua New Guinea (PNG), timber harvesting is occurring under policies and regulations that are intended to provide for a sustainable supply of timber from designated forest management areas (FMA). These operations are largely undertaken by international companies for the log export market. There is considerable concern about the sustainability of current management practices, the recovery of forests after harvesting and the potential of forests to provide timber or other community needs (Filer et al., 2009; Shearman et al., 2009).

The forests of PNG are a widespread and valuable long-term national asset, however, the current rate of harvest is considered unsustainable and the capacity of these forests to either recover or degrade after harvesting is not well understood and remains uncertain. The current status of selectively harvested forest in PNG is such that, areas harvested through logging increased from 850,000 ha in 1992 to over one million ha in 1995 (Bun, 1992; Nir 1995). Recent Papua New Guinea Forest Authority (PNGFA) statistics also indicate that, from 1988 to 2007, the estimated area affected by commercial harvesting has increased to over 2 million ha and timber volume harvested in the form of logs during the same period was over 39 million m^3 (PNGFA, 2007). As it is now, selectively-harvested forests in PNG amount to 10% of forested areas and is generally considered to be degraded, and the timber industry has assumed that it has no current potential for timber production (Keenan et al., 2008). Some authors have suggested that selectively-harvested forest in PNG is subject to inadequate regeneration and is continuing to degrade over time (Shearman et al., 2010).

Much of the international debate about tropical forest harvesting and its impacts on forests are primarily around impacts on biodiversity (Kobayashi, 1992; Lamb 1998) and a global concern about lose of thousands of species through tropical deforestation, particularly in some of the world's biodiversity hotspots (Myers et al., 2000; Pimm and Raven 2000; Stork 2010). Like many other developing countries in the tropics, PNG's natural forests are being exploited at a rapid rate. It is estimated that primary forests are decreasing at a rate of 113,000-120,000 ha y^{-1} (FAO, 2005; PNGFA, 2003) through logging, agricultural activities, mining and other land uses. World Bank statistics estimated that from 1980 to 1990, the annual deforestation rate in PNG was 0.3% (Forestry Compendium, 2003). Between 1990 and 2000 the deforestation rate was estimated to be 0.44% and this has increased to 0.46% from 2000 to 2005 (FAO, 2005; 2007; ITTO, 2006). Other studies have suggested that the deforestation rate is currently about 1.4% y^{-1} (Shearman et al. 2008) although there is debate about this figure (Filer et al., 2009).

Much of the uncertainty about the rate of forest loss and the capacity of harvested forests to provide timber, sequester carbon or other community benefits is due to the lack of knowledge about the extent of impacts and rate of recovery of forests after harvesting. There have been a relatively limited number of studies of forest dynamics and changes in stand structure of tropical forests after harvesting (Breugel et al., 2006; Kobayashi, 1992; Nicholson, 1958; Nicholson et al., 1988). Most of the research in the area has focused on the rehabilitation and restoration of degraded areas after large-scale clearance for agriculture and subsequent abandonment or disturbances such as fire (for example, Lamb, 1998; Lanly, 2003; Shono et al., 2007). Other studies have focused on the impact of drought on tropical forest dynamics (Nakagawa et al., 2000), the impact of habitat fragmentation on forest-climate interactions (Laurance, 2004), and the study of changes in tropical forest structure and dynamics (Lewis et al., 2004).

In this study, we aimed to: (1) examine the impacts of selective timber harvesting on stand structure by analyzing the diameter and basal area (BA) distribution since harvesting, (2) assess the dynamics of cutover forest relating to trends in stand BA, residual timber volume and forest carbon stocks, (3) determine a critical threshold BA for forest recovery by testing a model developed in Queensland tropical forests to analyse BA growth for harvested forests, (4) assess the impact of the El Nino induced forest fire of 1997-1998 on BA growth and mortality rates of the burnt plots, and (5) investigate the impacts of harvesting on species diversity of cutover tropical forests in PNG.

We tested two hypotheses: that a critical threshold BA may exist that determines if a harvested forest degrades or recovers; and that the mean BA increment for plots measured <10 years and >10 years since harvesting are the same.

BA is a commonly used measure of forest stocking and stand structure and we use this measure as an indicator to determine whether a harvested forest degrades or recovers over time. We focus our discussions on the implications of this study for the future management of cut-over forests in PNG.

2. Materials and methods

2.1 PNGFRI permanent sample plots and data analysis

Currently 135 PSPs are being maintained by PNGFRI on lowland tropical forests of PNG with a measurement history extending over 15 years. The PSP network comprises of 122 plots on selectively-harvested forest with 411 measurements and 13 plots on unlogged forests with 23 measurements (Fox et al., 2010). Earlier work by Alder (1998) evaluated data from some of these plots and concluded that all the plots could be regarded as having rather similar floristic composition characteristic of the lowland tropical forests of PNG.

During the establishment of PSPs, plots were randomly located and established in pairs. All the plots are one hectare in size and divided into 25 sub-plots of 20 m x 20 m (Romijn 1994a). The field procedures for establishment and measurements of the plots were adopted from Alder and Synnott (1992). In the assessment of trees in the plot, a standard quadrat numbering system was used. This system uses quadrat numbers on the basis of coordinates or offsets from the plot origin, for example, south-west corner. During plot measurement, all tree species ≥10cm diameter at breast height (DBH) were assessed. Measurements taken on trees included dbh, height, crown diameter, crown classes according to Dawkins (1958), and an initial basal area count for each tree was undertaken using a prism wedge. For plots on selectively-harvested forest, the time period for their initial establishment and measurement after disturbance from harvesting activities ranges from immediately after harvesting to more than 10 years after harvesting. For plots accessible by road, re-measurements have been taken on an annual basis, while the initial re-measurement of the other plots were carried out on a two-year interval but have been re-scheduled for re-measurements on a five-year interval due to funding constraints.

For the purpose of this study, a total of 110 PSPs on selectively-harvested forest have been used. Of the total plots used, we selected 89 plots to analyse stand BA, residual timber volume, forest carbon and species diversity of selectively-harvested forest. These 89 plots were selected so that plots that were burnt by fire during the 1997-1998 El Nino drought; those with short measurement period; and plots affected by erroneous measurements were excluded from this particular analysis. To determine the mortality of plots severely burnt during the drought period, we isolated the 21 plots that were burnt by the fire and analysed them separately.

In our data analysis, we used MS Excel spreadsheet for processing PSP data and the statistical software used in the analysis included SPSS ver.18, SigmaPlot ver.11, and Minitab ver.15. Graphical outputs for our results have been generated from SigmaPlot and Excel spreadsheet.

2.2 Study Sites and PSP locations

Most of the plots have been recorded on lowland tropical forest types distributed throughout PNG as these are where most harvesting activities have taken place. Only two plots have been established in higher altitude montane forest dominated by the genera *Castanopsis* and *Nothofagus* in the Southern Highlands part of the country. 23% of PSPs are located on the island of New Britain as there are large areas of selectively-harvested forest. Majority of the plots are located on wet tropical climate and annual rainfall in these plots averages to over 3000 mm annum^{-1}. An earlier study to assess the relationship between the soil groups and species composition in the logged-over rainforests of PNG showed that; the four common soil groups found in most of the plots were Alfisols, Entisols, Inceptsols, and Mollisols (Pokana, 2002). A map of PNG (Fox et al., 2010) showing the study sites and PSP locations is shown in Figure 1.

Insert Figure 1 here.

2.3 Analysis of stand structure

The number of trees per hectare (stems ha^{-1}) and BA are measures of stand density and their distribution between diameter classes are often used to examine the structure of a stand. We analysed both of these measures in order to describe the impacts of harvesting on stand structure of natural forest in PNG. The trends in diameter and BA distribution since harvesting are represented by simple column graphs of diameter classes by number of stems ha^{-1} and BA (Figure 2). We also analysed the diameter and BA distribution of plots on the unlogged forest in order to make comparisons with the structure of selectively-harvested forest.

2.4 Assessing the dynamics of cutover forests

We assessed the harvesting impacts on the dynamics of cutover forest by analyzing stand BA, residual timber volume and aboveground forest carbon stocks in the plots. To examine the condition of the forest after harvesting, we established a relationship between time since harvesting (TSH) and mean BA. We estimated the MBA for each plot as shown below;

$$MBA_p = \frac{\sum\left[Ba_{i+j+k+\cdots}\right]}{\left[Y_f - Y_i\right]} \tag{1}$$

Where *MBA*$_p$ = mean basal area for plot *p, Ba* = basal area, *i* = starting plot Basal area after harvesting, *j* = second Ba measurement, *k* = third Ba measurement, and Y_f = year of final Ba measurement at year *f*, and *i = year of initial Ba measurement at year i.*

A linear regression analysis was carried out to examine the relationship between TSH and mean BA in order to examine the change in BA overtime after harvesting. We carried out similar analysis to determine the mean residual timber volume for trees ≥20cm DBH (MVOL) in each plot as follow;

$$MVOL_{p\geq 20cm} = \frac{\sum\left[Vol_{i+j+k+\cdots}\right]}{\left[Y_f - Y_i\right]} \tag{2}$$

Where $MVOL_{p\geq 20cm}$ = mean volume for plot p, Vol = volume, i = starting plot volume after harvesting, j = second volume measurement, k = third volume measurement, and Y_f = year of final plot volume at year f, and i = year of starting volume at year i.

To determine the aboveground live biomass ($\text{AGLB}_{\geq 10\text{cm}}$) in order to assess the forest carbon of harvested forest in each plot, we used a model developed by Chave et al. (2005). The AGLB for each tree $\geq$10cm DBH was determined and then converted to forest carbon using a conversion factor of 0.5 (trees are 50% carbon by weight). Our estimate of forest carbon here is based on AGLB for trees$\geq$10cm DBH only and does not include the unmeasured pools such as $\text{AGLB}_{<10\text{cm}}$, fine litter (FL) and course wood debris (CWD). We also did not consider the belowground biomass (BGB) in this study. For a detailed study of assessment of forest carbon in primary and selectively harvested tropical forest in PNG, refer to Fox et al. (2010). In our study here of $\text{AGLB}_{\geq 10\text{cm}}$, we carried out similar analysis as with the change in BA and residual timber volume over time for harvested forest. We established the relationship between TSH and aboveground forest carbon to examine the average trend of this measure since harvesting.

The model by Chave et al. (2005) which we have applied to estimate $\text{AGLB}_{\geq 10\text{cm}}$ takes the form as shown below;

$$AGLB_{\geq 10\text{cm}} = 0.0776[pD^2TH]^{0.940} \qquad (3)$$

Where $AGLB$ = aboveground live biomass, ρ = wood specific gravity, and D = tree diameter.

In our analysis to assess the dynamics of cutover forest, our preliminary investigation to test the normality of Y-response variables (BA, VOL, AGLB) and X-independent variable (TSH) showed that; our data were homogeneous and normally distributed although a scatter plot suggested a higher variability in the dataset. Examination of residual plots in our preliminary investigation of our data also showed similar results hence, we did not consider necessary to transform the dependent variables to stabilize the variance. To address this issue, we summarised our dataset in simple pivot tables using MS Excel spreadsheet and mean values of the variables were then further analysed. We also note from the study of degradation of forests through logging and fire in the eastern Brazilian Amazon (Gerwing, 2002) that, high variances inherent in sampling degraded forests are common in tropical forests.

2.5 Basal area and volume growth

In this study, we used the data from the 89 PSPs measured on selectively-harvested forest to determine the MBAI and VOLI for each plot. To address our first hypothesis that; a critical threshold BA may exist that determines if a harvested forest degrades or recovers, we tested a model developed for native tropical forest in Queensland (Vanclay, 1994) and carried out a logarithmic regression analysis to establish the relationship between the starting BA (SBA) after harvesting and MBAI. Establishing this relationship allowed us to determine whether the forest was recovering (positive trend in BA); degrading (negative trend in BA); or neither recovering nor degrading (constant BA). This model takes the form as shown below;

$$\boldsymbol{ln\Delta G = -3.071 + 1.094\, ln\, G + 0.007402\, G\, S_{h,d} - 0.2258\, G} \tag{4}$$

Where, ΔG = stand basal area increment, G = stand basal area (m^2 ha-1), $S_{h,d}$ = estimate of site productivity based on height-diameter relationship.

Fox et al. (2010) developed species-specific height-diameter models for PSPs in natural tropical forests in PNG. We incorporated the average total tree height in PSPs from his work to test the above model and estimated the stand basal area increment in our study.

We also determined MBAI for plots with an increasing BA (68 plots) and those with decreasing BA (21 plots) in order to examine the trend in MBAI after harvesting. To examine the average trend in MBAI after harvesting, we established a relationship between mean TSH (MTSH) and MBAI represented by a scatter with line plot and error bars. We tested the second hypothesis that; MBAI for plots measured <10 years and >10 years since harvesting is equal by carrying out a two-way ANOVA. Result for this test was insignificant (p = *0.94)* thus, details are not reported in the results section.

We considered environmental factors such as rainfall and altitude to have affected BA growth hence, we also carried out correlation analysis to establish whether or not an association existed between these two variables and BA growth. Our tests here showed insignificant results (pearson's correlation $\boldsymbol{p}$ = 0.124, for rainfall and MBAI and $\boldsymbol{p}$ = -0.04 for altitude and MBAI) so we did not report the details in the results section. A two-way ANOVA test also showed that there was no significant difference between MBAI for plots on higher rainfall sites (>3000mm yr^{-1}) and those on lower rainfall sites (<3000mm yr^{-1}) ($p = 0.137$).

To assess the trend in timber yield since harvesting, we tested a model developed in the Philippines which is based on an empirical function of initial basal area, site quality and time since logging (Mendoza and Gumpal, 1987; Vanclay, 1994). The equation takes the form;

$$\boldsymbol{\ln V_t = 1.34 + 0.394 \ln Go + 0.346 \ln t + 0.00275\, S_h\, t^{-1}} \qquad (5)$$

Where $\ln V_t$ = timber yield ($m^3\ ha^{-1}$), t = years after logging, G_o = residual basal area ($m^2\ ha^{-1}$) after logging, S_h = site quality (m) estimated as the average total height of residual trees.

To apply the model in our study, we used the average total tree height estimated from the analysis of PSPs in tropical forests in PNG from the previous study of Fox et al. (2010). We carried out a log linear regression to establish the relationship between TSH and timber yield of harvested forests.

2.6 Mortality due to the 1997-1998 El Nino drought

A total of 21 PSPs were burnt by forest fires during the 1997-1998 El Nino drought in PNG. We isolated these plots from the total of 110 plots used in this study to determine mortality rates in the burnt plots in order to assess the impact of fire on BA growth of harvested forests. In this particular analysis, we estimated annual mortality rates for eight of the plots that were severely burnt by fire during the drought period. In this case we used the following formula to determine annual tree mortality rates (Nakagawa et al., 2000);

$$m = \left[1 - \left(\frac{D}{X}\right)^{\frac{1}{n}}\right] * 100 \qquad (6)$$

Where; X is initial number of tree individuals or BA, D is number of dead trees or lost BA during n years. For the purpose of this study we used lost BA for two consecutive re-measurements before and after the fire in order to determine annual tree mortality rates caused by fire during the El Nino drought.

2.7 Shannon-wiener index (H^1)

To examine the impact of harvesting on species diversity, we estimated the Shannon-Wiener Index (H^1) (Nicholson, 1998; Williams, 2007) for all tree species. The Shannon-Wiener Index (H^1) is a measure of species diversity determined from the relative abundance of species in a community as taken from Williams (2007) and takes the form;

$$H^1 = -\sum_{i=1}^{s} pi \, ln \, pi \tag{7}$$

Where $p_i = n_i/N$, n_i is the number of individuals present of species i, N is the total number of individuals, and s is the total number of species. Here we determine the Shannon-Wiener index for tree species ≥10cm DBH for plots that have been disturbed from harvesting to demonstrate the impact of this activity on species diversity.

3. Results

3.1 Diameter and basal area distribution since harvesting

Analysis of stand structure after harvesting showed that there is significant increase in stem numbers in the lower diameter classes (10-29cm DBH) while there is almost absence of trees in the larger size classes (>70cm DBH). This is as expected because the selective harvesting practice in PNG is such that; majority of the trees ≥50cm DBH are removed during logging. The distribution of BA since harvesting on the other hand, shows significant increase in BA in almost all size classes. This indicates the evidence of recruitment of smaller size class stems into the ≥10cm DBH class and ingrowth and related diameter increment occurring in the larger diameter classes. As expected, the distribution of number of stems and BA among diameter classes showed a *reverse-J* pattern.

Our analysis of the diameter and BA distribution in unlogged plots showed that; there was no marked increase in the number of stems in the range of diameter classes (≥10cm to 90cm+ DBH). While there was also no marked increase in BA in the smaller size classes (≥10cm to 49cm DBH), there was evidence of BA increase in the larger diameter classes (≥50cm DBH) . We did not report the details of our analysis of the diameter and BA distribution of unlogged plots however, the number of stems for all size class (≥10cm DBH) averaged to 531 stems ha^{-1}±138 *(SD)* in unlogged plots and 351 stems ha^{-1}±100 *(SD)* in logged plots. Average BA was 29.01m^2 ha^{-1}±5.77 *(SD)* and 17.95m^2 ha^{-1}±4.49 *(SD)* in unlogged and logged plots respectively.

Figure 2 (a) and (b) are the diameter and BA distribution for cutover forest.

Insert Fig. 2 (a) and (b) here.

3.2 *Trends in stand basal area*

The graph of TSH by BA shows that there is higher variability about each data point for longer time since harvesting because of few measurements and because the increment trajectory varied considerably between plots (Fig. 3a). The relationship between TSH and BA was weak (r^2= 0.09) because of the variability in the data however, in order to address this variability, mean values of BA were summarised in the pivot table and a linear regression analysis showed a strong relationship (r^2 = 0.80) between TSH and BA (Fig. 3b). In this case, the average trend in BA across all plots showed a consistent recovery of natural forest after timber harvesting (Fig. 3b). Overall, there is an increasing BA over time since harvesting suggesting that, in general, these forests are recovering after harvesting.

Insert Figure 3 (a) and (b) here.

3.3 *Average trends in residual timber volume and aboveground forest carbon*

While earlier analysis (Figure 3 (a) indicated higher variability in the data for the 89 plots, mean plot values for timber volume and aboveground forest carbon summarised in the pivot table and presented in the form of a regression analysis (Figure 4 (a) and (b) shows that both of this variables increased in a positive trend over time since harvesting. Regression here is significant for TSH by average timber volume ($r^2 = 0.56, p<0.05$) as well as for TSH by average forest carbon ($r^2 = 0.75, p<0.05$).

Insert Figure 4 (a) and (b) here

3.4 *Critical threshold basal area for recovery of harvested forest*

Results from testing a model (equation 4) developed in Queensland (Vanclay, 1994) using our data showed a strong relationship between the starting BA after harvesting and mean BAI ($r^2 = 0.75, p<0.05$) (Figure 5). Test of our hypothesis that; a critical threshold BA may exist that determines if a harvested forest degrades or recovers using this model showed that; although there is a positive increase in BA growth, this relationship did not establish a single critical threshold BA for cutover forests to either recover or degrade. Our analysis here suggests that, there did not appear to be a critical threshold BA at which harvested forests could be considered to either degrade or recover. We consider that, given the short measurement period of these plots, re-measurements of these plots for a longer period of time would have yielded better results as far as our hypothesis is concerned. Graphical output from the model using logarithmic regression analysis is shown in Figure 5.

Insert Figure 5 here.

3.5 *Basal area growth since harvesting*

For plots with an increasing BA, mean BAI was 0.42m^2 ha^{-1} y^{-1} *(SD 0.41)* while for plots with falling BA, BAI averages to -0.58m^2 ha^{-1} y^{-1} *(SD 0.52)*. The mean BAI across all plots (89 PSPs) was 0.18m^2 ha^{-1} y^{-1} *(SD 0.61)*. Table 1 gives details of the impact of harvesting on MBAI

Insert Table 1 here.

The scatter plot showing line with markers and data points with regression and error bars in Fig. 6 represent the average trend in natural log MBAI (LnMBAI) after harvesting. The data points are the mean BAI at each time period since harvesting while the error bars in this case represent standard deviation from the mean. MBAI increased almost consistently throughout the plot measurement period. In this case, the relationship between MTSH and LnBAI is significant $(r^2 = 0.05, p<0.05)$. Results from a two-way ANOVA also showed that there was no significant difference in MBAI for plots measured <10 years and those measured >10 years after harvesting $(P>0.05)$. Fig. 6 shows the representation of average trend in MBAI since selective timber harvesting.

Insert Figure 6 here.

3.6 Timber Yield Since harvesting

Our test of the model (equation 5) developed in the Philippines tropical forests (Mendoza and Gumpal, 1987; Vanclay, 1994) to assess the trend in timber yield since harvesting showed a strong relation between TSH and timber yield of residual stand $(r^2 = 0.85, p<0.05)$. Results here showed that timber yield of harvested forest in the natural forest of PNG averages to 1.08m^3 ha^{-1} ± 0.08 and gradually increases over the measurement period while mean volume increment is estimated at 2.38m^3 ha^{-1} yr^{-1} ± 7.88. The model output from the logarithmic regression analysis showing the relationship between TSH and natural log timber yield *(LnVt)* is shown in Figure 7.

Insert Figure 7 here.

The different components of selectively-harvested natural forests in PNG, estimated based on our analysis of the 89 PSP data are summarised on Table 2.

Insert Table 2 here.

Many studies have been carried out in other tropical regions to assess the dynamics of natural tropical forests. While we did not consider most of those studies, our results are compared with only few of the studies which directly relate to assessing the impact of selective logging on the dynamics of natural forests, focusing on impact of logging on change and growth of BA. Table 3 is the comparison of the results from our study with similar studies carried out in other tropical regions.

Insert Table 3 here.

3.7 Mortality due to the fire caused during the 1997-1998 El Nino drought

The mortality rates of each plot were estimated using equation (6) according to Nakagawa et al. (2000). Of the 21 plots burnt during the drought period, 38% of the plots (8 plots) were severely affected with high mortality rates due to the fire. The affected plots are in Central New Ireland (Cnird01, Cnird02); Iva Inika (Ivain01, Ivain02); Kapuluk (Kapul01, Kapul02); and Wimare (Wimar01, Wimar02). Almost all the plots had increasing BA before the fire (Fig. 8). An exception was Wimar02 that showed declining BA before the fire with a more pronounced decline in annual mortality rates after that date. The average annual mortality rate for the 8 severely burnt plots was 16.21% y^{-1} ± 8.61. The worst affected plots were in Central New Ireland (CNIRD 01, CNIRD02); Central (IVAIN01); West New Britain (KAPUL01, KAPUL02); and Western province (WIMAR02). Fig. 8 is the column graph with error bars representing annual mortality rates for the eight plots severely burnt by fire during the 1997-1998 El Nino drought period.

Insert Figure 8 here.

3.8 Shannon-Wiener Index for cutover forest

The Shannon-Wiener Index (H^1) for all tree species in each plot was determined from equation (7) (Nicholson, 1998; Williams, 2007). Our analysis suggested that, species diversity indicated by the Shannon-Wiener Index has remained almost constant since harvesting, at an average of about 3.5 ± 0.33 (Fig. 9). For plots with the longest measurement history (24 years) species diversity has not increased and the index remained almost constant over this period. In this case the relationship between TSH and Shannon-Wiener index is not significant over time $(r^2 = 0.12, p = 0.07)$.

Our analysis of the Shannon-Wiener Index for plots on unlogged forest showed similar trends and insignificant results although the index was higher (4.9 ± 0.21) than plots on logged-over forest. Details of the analysis of the indices for unlogged plots are not reported in our study.

Fig. 9 shows the change in Shannon-Wiener Index over time for plots on logged-over forest.

Insert Fig. 9 here.

4. Discussion

The number of trees per hectare, basal area, volume or various stand density indices are measures of stand density (Davis and Johnson, 1987). Often the distribution of the number of tree stems between diameter size classes and distribution of individual stems amongst basal area size classes are the measures used to examine the structure of a stand which are more informative. BA is often an important measure of stand density and its distribution may be one of the quickest means to assess forest structure after timber harvesting. As well as that, size class distribution of individual tree species in a stand is also useful to examine the structure of the stand. Our analysis of the impact of selective timber harvesting on stand structure showed that, the number of stems increased in the smaller size classes while stand BA increased in almost all size classes over the plot measurement period (Fig.2 a and b). Similar trends were observed by Yosi (2004) in his study of the impact of logging on short-term trends in forest structure, composition and population of lowland tropical forest in PNG. Trends in the diameter and BA distribution in our study here may provide evidence of higher recruitment in the smaller diameter classes (10-49cm dbh) and ingrowth occurring in the larger size classes (50cm+ dbh). The overall distribution of the number of stems and BA among diameter classes in our study here is represented by the negative exponential *reverse-J* pattern, which is a typical characteristic of the uneven-aged mixed natural forest stands (Dawkins, 1958; Davis & Johnson, 1987; Ohara, 2002).

Results from analysis of impact of harvesting on stand dynamics of cutover forests showed that, there was consistent increase in stand BA (Fig. 3 b), residual timber volume and aboveground forest carbon (Fig. 4 a and b) over the plot measurement period. In PNG's natural forests, earlier research studies indicated that BA in undisturbed forests was about 30-32m^2 ha^{-1} (Alder, 1998; Oavika, 1992; Kingston and Nir, 1988). In the present study, we found that average BA in plots on forests disturbed from logging is about 18m^2 ha^{-1}, a reduction of about 40% from the original unlogged forest.

When we compared the change and growth in BA since selective logging from our study with similar studies in tropical forests in other regions (Table 3), results from our study here are within the ranges of those studies. For example, similar to studies carried out by Nicholson et al. (1988) in north Queensland rainforest showed that, BA was reduced due to selective harvesting by between 8% and 43%. Similar studies of Smith et al. (2005) and Pelissier et al. (1998) also showed similar figures for BA in unlogged and logged forests. Although the MBAI after selective logging in our study is lower (0.18-0.04 m^2 ha yr^{-1}) than that of the study by Smith et al. (2005) (0.32-0.75 m^2 ha yr^{-1}), overall stand BA continued to increase over the plot measurement period (Fig. 3 b). As indicated in our study, the consistent increase in BA after harvesting (Fig. 3 b) suggests that selectively-harvested forests in PNG have the potential to recover due to relatively lessened mortality and enhanced recruitment and tree growth following harvesting. This has also been observed in other regions (eg. north Queensland rainforest, see Nicholson et al. 1988). Average trend in BA in this study is similar to that of Williams et al. (2008). Their studies were not related to commercial harvesting activities but indicated that after slash and burn agriculture there were significant relationships between the period of re-growth of garden areas and BA.

If the plots in this sample are generally representative of cut-over forests in PNG, the change in BA over time in this study suggests that a significant proportion of native forests in PNG are recovering after disturbance from conventional harvesting. This contrasts with the suggestion of (Shearman et al., 2009) that harvested forests in PNG are permanently degraded. In the present study we show through direct evidence from ground-based monitoring of PSPs, that a relatively high proportion of harvested native forests in PNG are generally recovering over time.

The increase in residual timber volume and aboveground forest carbon since selective timber harvesting is due to growth in terms of diameter increment, ingrowth and increase in biomass of the residual stand.

Results from testing the model developed for Queensland tropical forests (equation 4) (Vanclay, 1994) to determine BA growth in our study showed that, there was a marked increase in SBAI ($r^2 = 0.75, p<0.05$) in the harvested tropical forests of PNG. When we tested the model to address our hypothesis that, a critical threshold BA may exist that determines whether a harvested forest degrades or recovers, results here suggested that, there is no critical threshold BA for forest recovery after harvesting. Although model output from our analysis (Fig. 5) shows that there is a consistent increase in SBAI over the range of STBA after harvesting, there is no evidence of a single critical threshold BA at which the BA growth decreases, indicating the condition of forest to either degrade or recover. Although there does not appear to be a critical threshold BA for forest recovery, earlier studies in PNG suggested that stands with BA below 25m^2 ha^{-1} should be allowed to recover to at least their original stocking before harvesting (Alder 1998). Regression analysis in Fig. 6 showing the relationship between TSH and SBAI also indicates significant increase ($r^2 = 0.50, p<0.05$) in SBAI of harvested forest.

When we tested the model developed in the Philippines (Vanclay, 1994; Mendoza and Gumpal, 1987) to examine the trends in timber yield of natural tropical forests in PNG since harvesting (Fig. 7), there was a strong relationship between TSH and timber yield ($r^2 = 0.85, p<0.05$). Average timber yield for selectively harvested forest generated from the model, using our PSP data from the 89 plots was 1.08m^3 ha^{-1} ± *0.08*.

There are some areas in PNG that are usually very wet all year round. For example, the Pomio area in East New Britain and Morere in Gulf province have rainfall exceeding 5000mm yr^{-1}. In our study, 49% of PSPs were located on areas with very high annual rainfall between 3000mm yr^{-1} and over 5000mm yr^{-1} and 51% in lower rainfall areas (<3000mm yr^{-1}). Our test to determine whether an association exists between rainfall and BA growth failed to yield significant results (pearson's correlation ***p*** = 0.124). Here we did not discuss in detail, the results of this analysis however, this may suggest that, those plots on high rainfall sites had poor drainage and these sites may have been water-logged which had affected BA growth. This particular situation may suggest that, high precipitation is probably a limiting factor for BA growth in harvested forests.

Some parts of PNG have drier forest types that when subject to periodic fire, readily converts to savannah and this often affects forest in proximity to settlements (Alder, 1998). During the period 1997-1998, 21 plots were burnt by forest fires however, they have been re-measured to monitor the impacts of fires on forest growth and condition. Our study of the eight plots severely burnt by fire during the drought period provides evidence that forest fires caused a reduction in BA due to mortality, which interferes with forest recovery after harvesting. In this study we showed that before the drought, mortality in the PSPs of Cnird02 and Kapul02 were -1.12% yr^{-1} and -2.17% yr^{-1} respectively however, mortality due to fire caused during the drought period in these two plots had increased dramatically to 24.89% yr^{-1} and 21.89% yr^{-1} respectively

(Fig. 8). A similar study by Nakagawa et al. (2000) on the impact of severe drought associated with the 1997-1998 El Nino in a tropical forest in Sarawak showed that; in a core plot mortality during non-drought period was 0.89% yr^{-1} and during the drought period, this was increased to 6.37% yr^{-1} in the same plot. Their study also indicated that the BA lost in the drought interval (1997-1998) was 3.4 times that of the annual BA increment of the measurement period 1993-1997. Annual mortality rates assessed as BA losses in our study here are considered higher than the Nakagawa et al. (2000) study as this may be probably due to the severity of the 1997-1998 El Nino forest fires that swept across many parts of PNG.

Tropical forests are characterized by a high diversity of woody species (Clark and Clark, 1999) as is the case in PNG. Species diversity is best indicated by the Shannon-Wiener Index, H^1 (Stocker et al., 1985). Studies carried out in north Queensland showed that timber harvesting had only a minimal affect on species diversity (Nicholson et al., 1988) and this was due to reduction in number of species. In the present study, analysis of species diversity shows that, selective timber harvesting does not affect species diversity. In this case, the Shannon-Wiener Index since harvesting is almost constant over time (Fig. 9). This may be because PNG’s tropical forests have a very high diversity of tree species and selective-harvesting removes only a few commercial timber species. Similar studies carried out by Nicholson et al. (1998) in north Queensland rainforests suggested that, after harvesting, as mortality exceeds the rate of recruitment, there is a trend to lower species richness and BA and such decline may also result from climatic trends and drought events. This may be the situation in PNG’s natural forest, as immediately after harvesting, mortality rates are usually higher and with debris created on the forest floor during harvesting, fire risks are also high. In Mozambique a study by Williams et al. (2008) found that the lowest Shannon indices occurred in the most recently abandoned slash and burn area and increased with time since abandonment. Their studies showed that, with a slash and burn type of agriculture, the Shannon indices appeared to increase over time since abandonment of the cleared area for garden. This is not the case in selective-harvesting in native forests of PNG where the index remains almost constant over time (Fig. 9).

5. Conclusions

This study of 89 large-scale PSPs demonstrated that there is a high degree of resilience following timber harvesting in native forests in PNG. BA increment after harvesting was positive on 68 (76%) of 89 plots and the average BA increment on these plots was 0.42 m^2 ha^{-1} yr^{-1}. Average BA increment across all plots over up to 25 years after harvesting was 0.18 m^2 ha^{-1} yr^{-1}. Recovering plots are therefore likely to reach the BA of undisturbed stands within 70 to 100 years. There did not appear to be a single critical threshold BA to determine whether harvested forests may recover or degrade however, given the short measurement period of the plots that we have studied, measurement of these plots for a longer time series is anticipated to yield better results. The positive trend in BA over time provides evidence that tropical forests of PNG have the potential to recover after disturbances from selective timber harvesting. However the response of these forests after harvesting is variable due to the intensity of harvesting, the response capacity of different species and environmental factors such as rainfall, altitude and drought-related fires. In this study we found that; BA is affected by the high mortality rates caused by the 1997-1998 El Nino related fire across PNG and areas with high precipitation also affected BA growth. As timber harvesting practice in PNG tends to select only those valuable commercial tree species, it is found that this type of selective system does not affect species diversity in PNG tropical forests. The future fate of these forests will depend on the period of time before future timber harvests and the effects of activities undertaken by communities living near the forest, such as subsistence gardening that result in a change in land cover or species composition. The condition of this type of forest is unlikely to attract large-scale commercial harvesting. There is a need for development of appropriate strategies and options for sustainable future management of cutover forests in PNG focusing on community-based forest management and utilisation.

Acknowledgements

The PNG Forest Authority (PNGFA) and its Forest Research Institute (PNGFRI), and the International Tropical Timber Organisation (ITTO) are acknowledged for the use of their permanent sample plot dataset for this study. The corresponding author and a team from PNGFRI were extensively involved in the permanent sample plot data collection funded by ITTO from 1993 to 1999; and by the Australian Centre for International Agriculture Research (ACIAR) from 2000 to 2007 (currently re-measurements are still being funded by ACIAR) prior to him pursuing postgraduate studies at The University of Melbourne. PNGFRI staff in the Sustainable Forest Management Research section who assisted in the permanent sample plot data collection are gratefully acknowledged.

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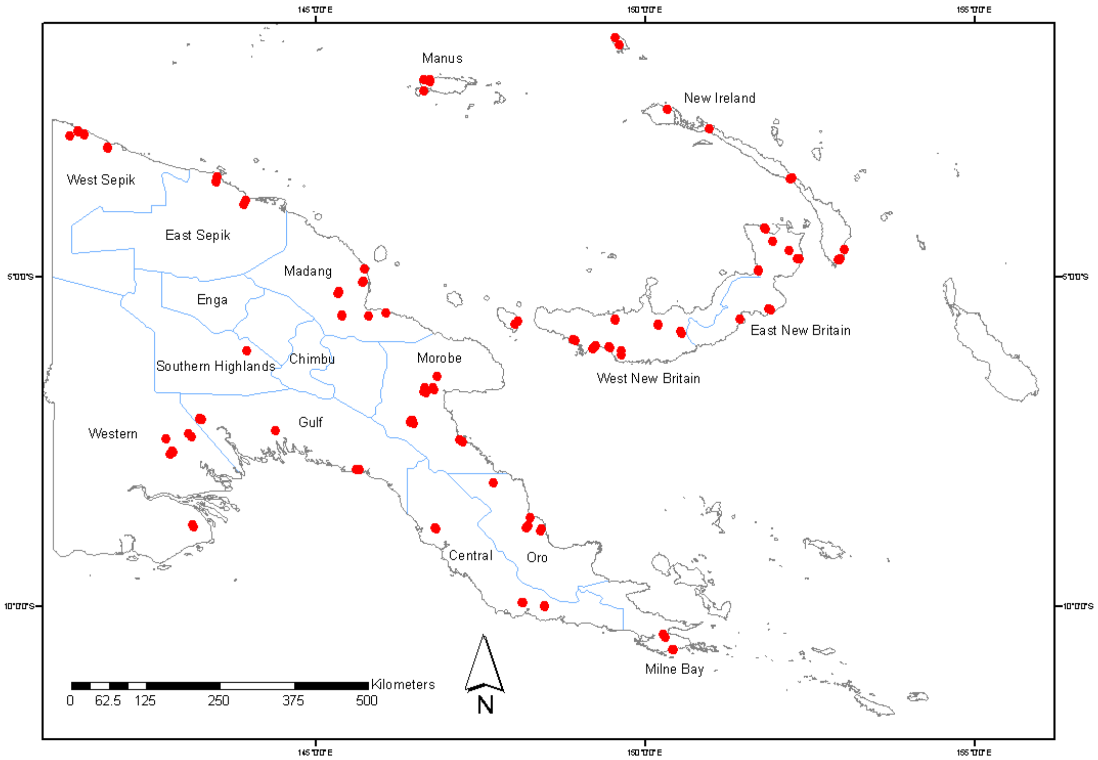
List of Figures

Figure 1:



(adapted from Fox et al., 2010)

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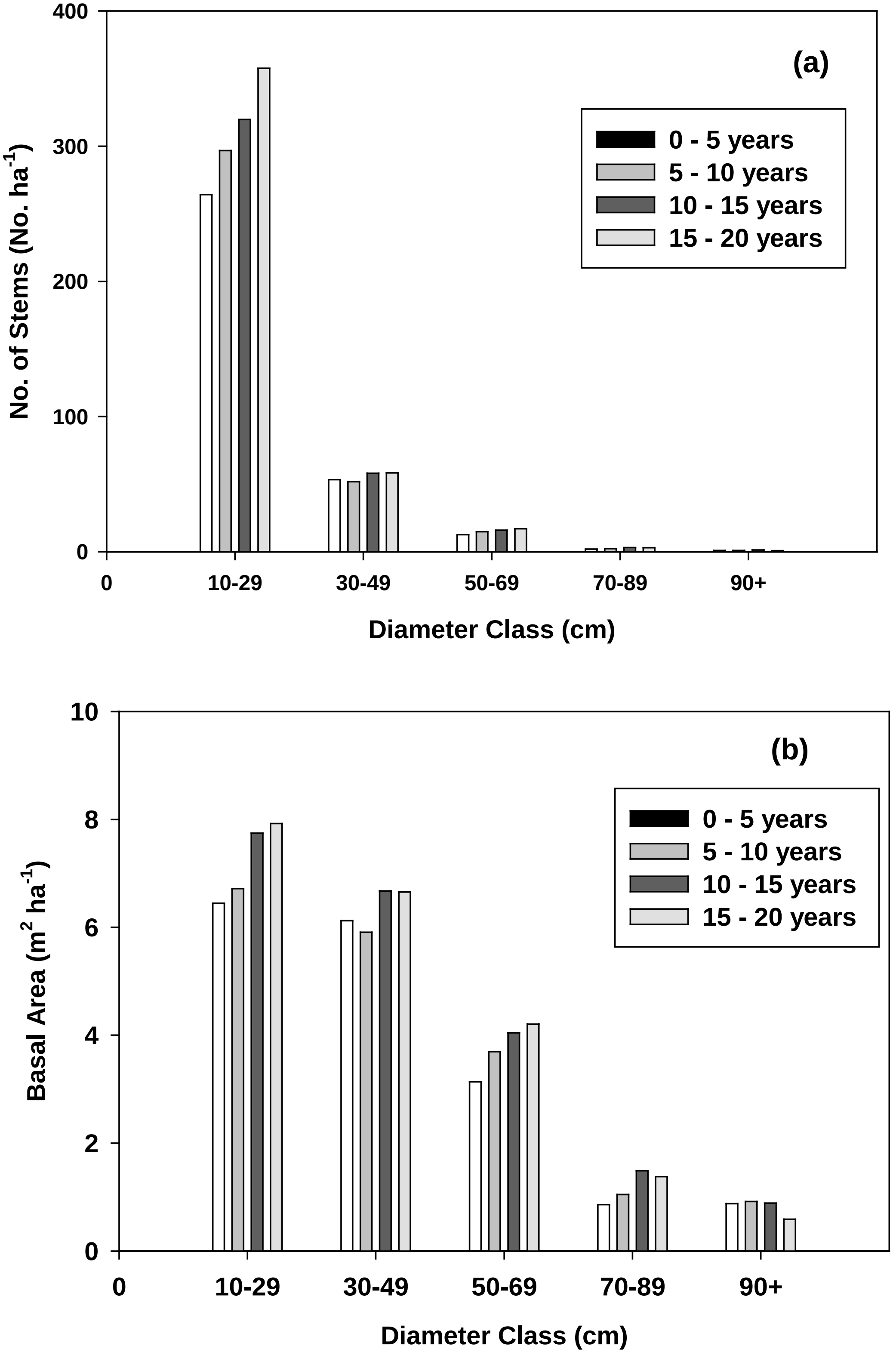

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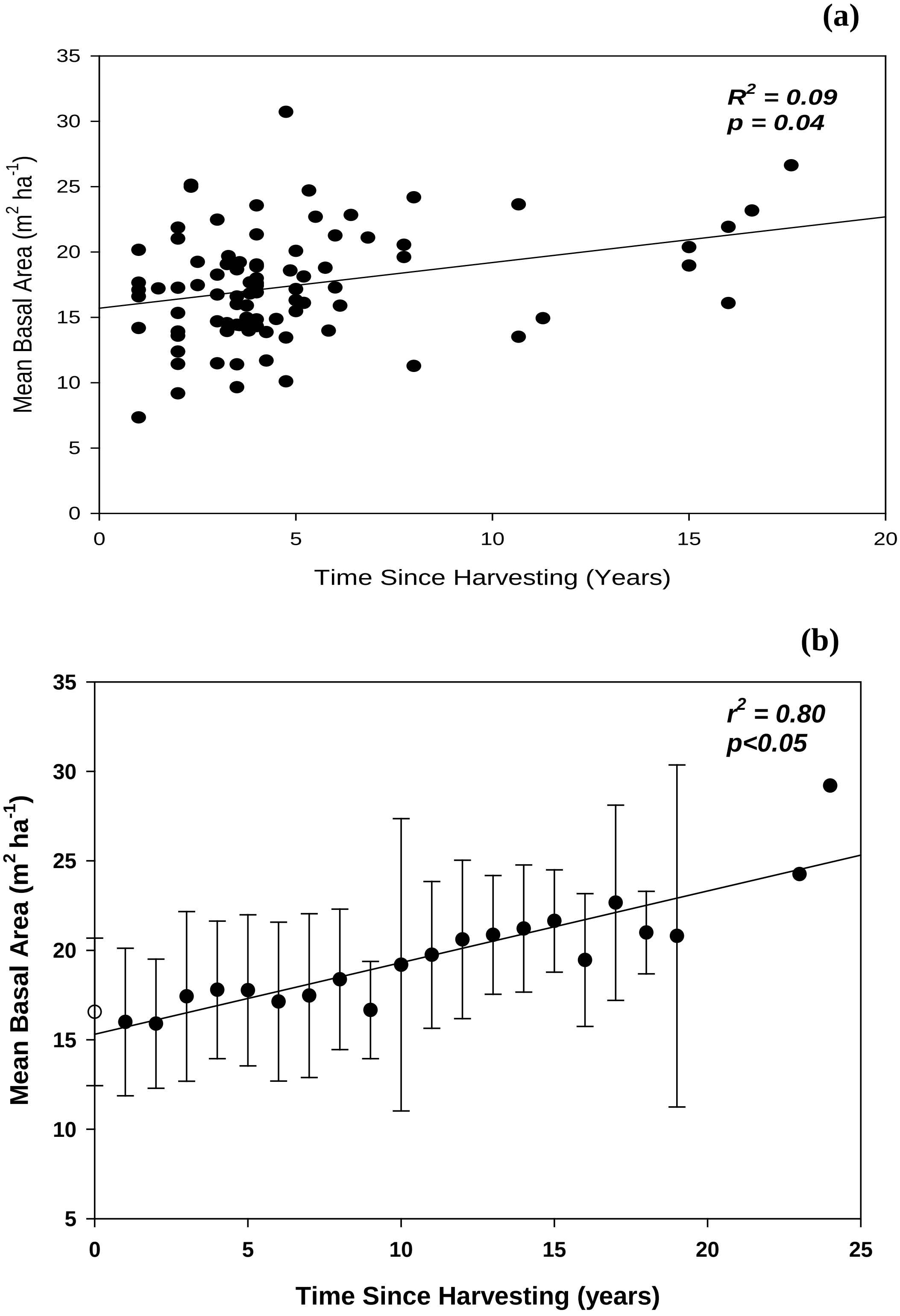

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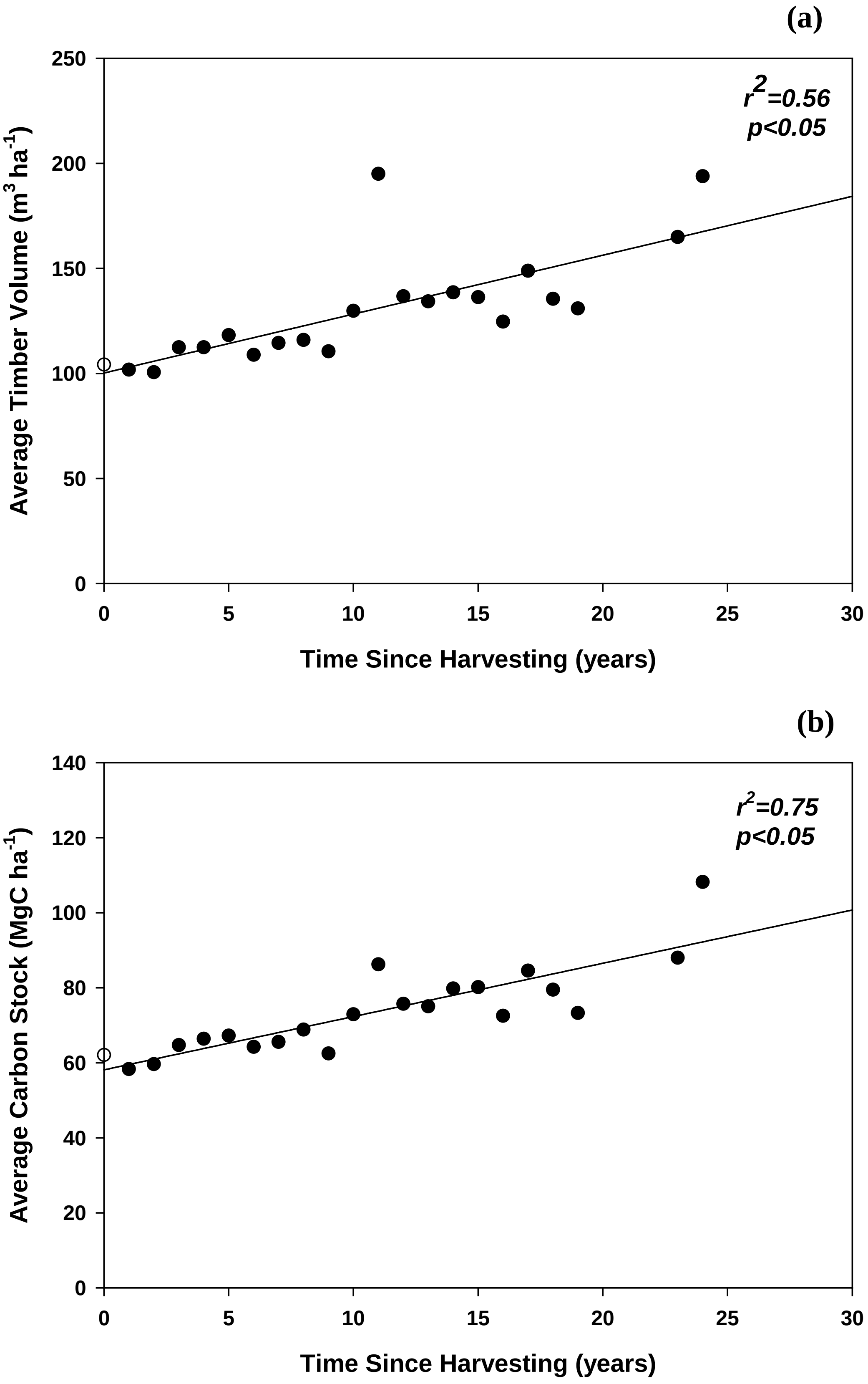

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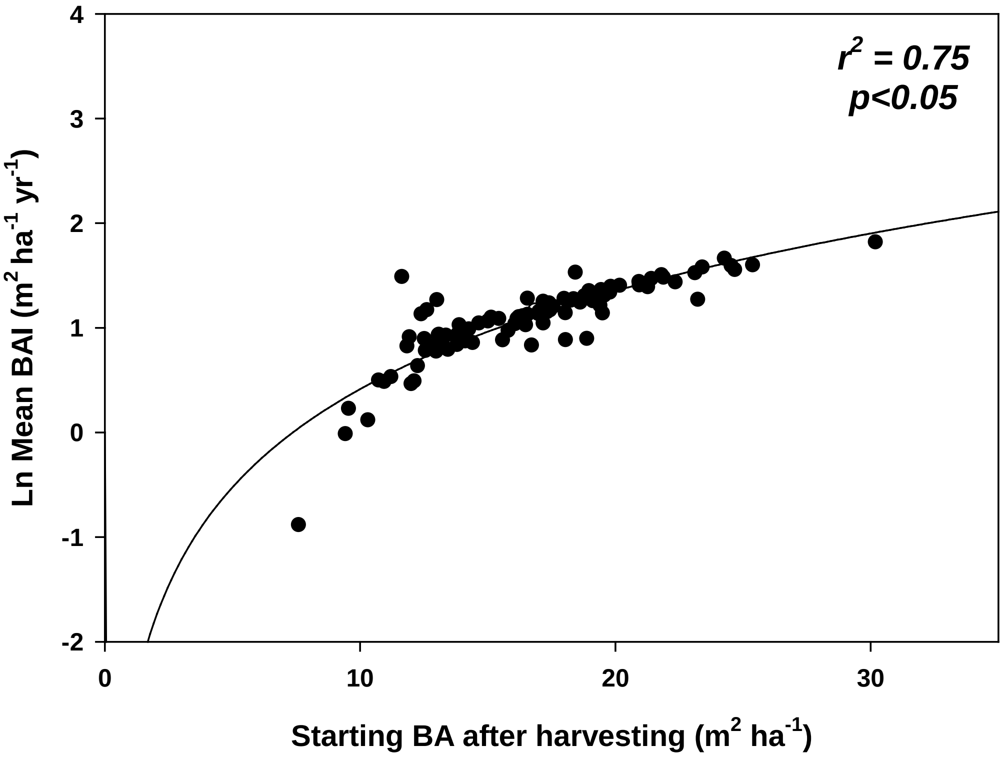


$r^2 = 0.75$
$p<0.05$
Ln Mean BAI (m^2 ha^{-1} yr^{-1})
Starting BA after harvesting (m^2 ha^{-1})
4
3
2
1
0
-1
-2
0
10
20
30

Figure 6:

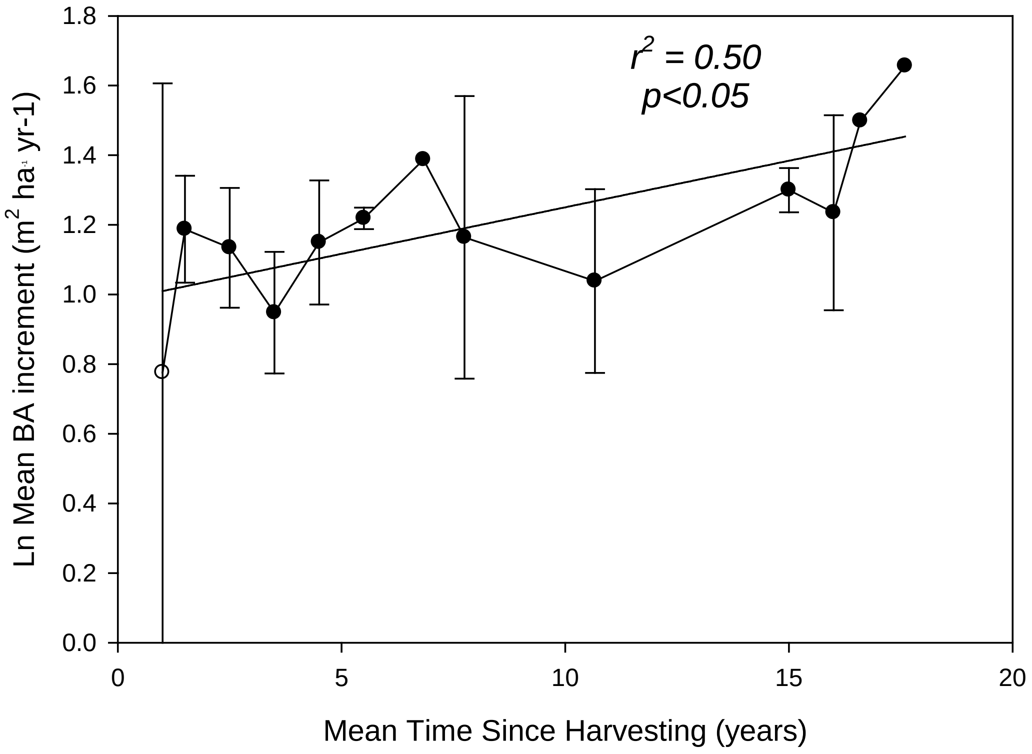
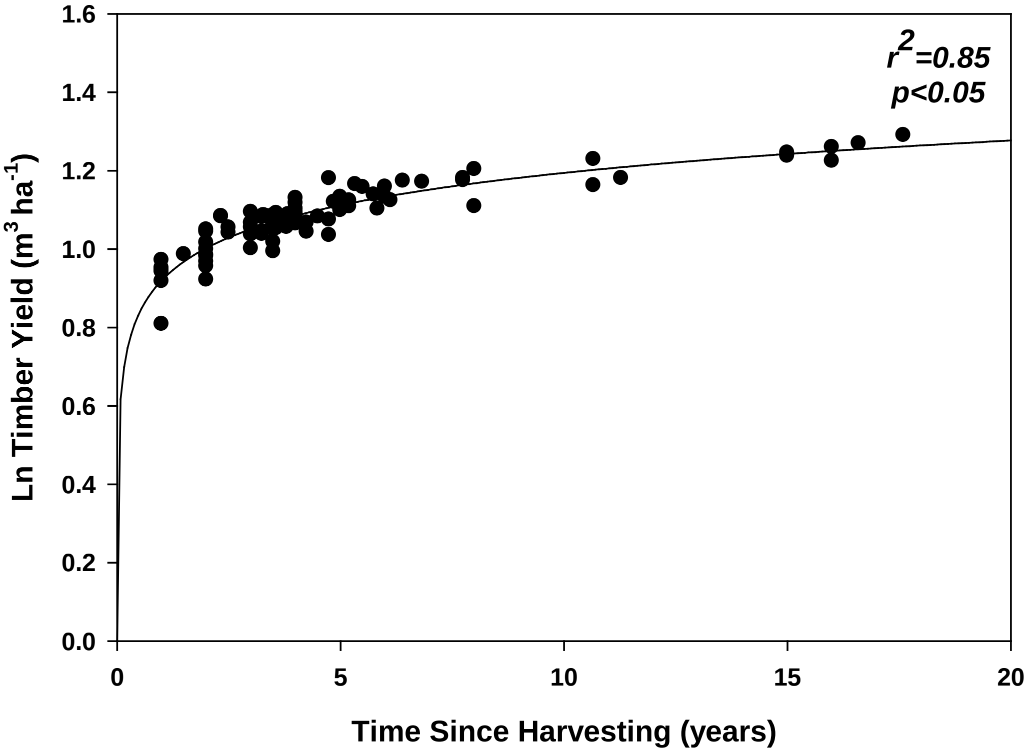
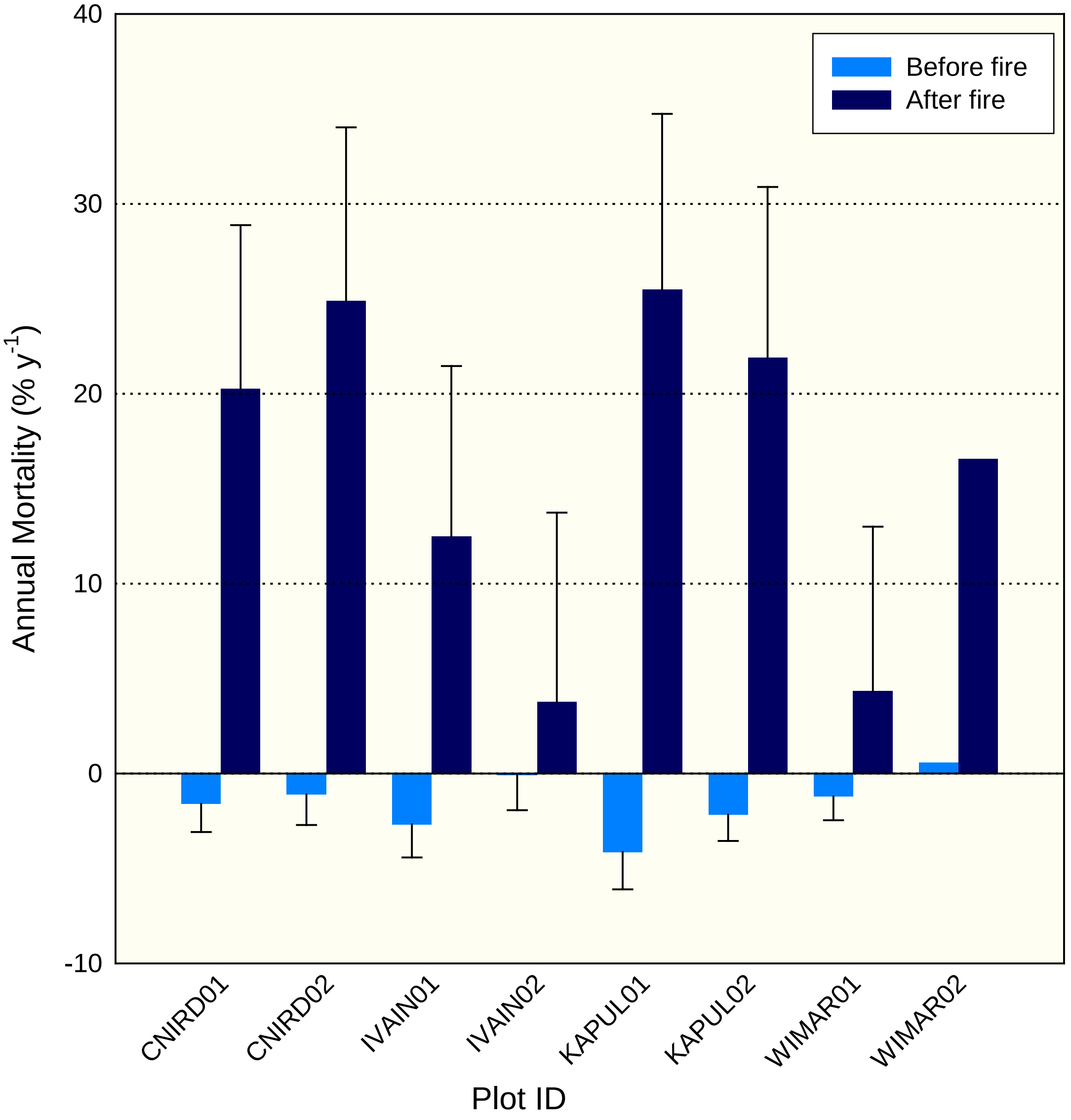

r² = 0.50
p<0.05
Ln Mean BA increment (m² ha⁻¹ yr-1)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Mean Time Since Harvesting (years)

Figure 7:



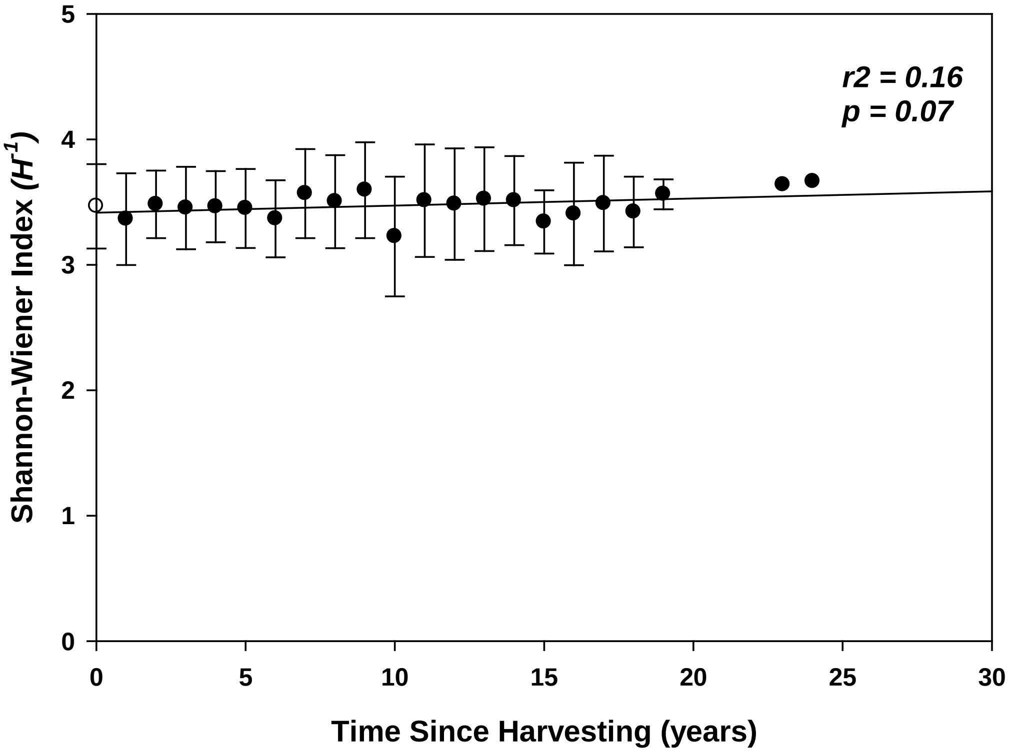
$r^2=0.85$
$p<0.05$
Ln Timber Yield ($m^3\ ha^{-1}$)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Time Since Harvesting (years)

Figure 8:



40
30
20
10
0
-10
Annual Mortality (% y^{-1})
Before fire
After fire
CNIRD01
CNIRD02
IVAIN01
IVAIN02
KAPUL01
KAPUL02
WIMAR01
WIMAR02
Plot ID

Figure 9:


r2 = 0.16
p = 0.07
Shannon-Wiener Index (H^{-1})
0
1
2
3
4
5
0
5
10
15
20
25
30
Time Since Harvesting (years)

List of Tables

Table 1: Mean BAI for plots with increasing and falling BA for the different conditions of selectively-harvested natural tropical forest in PNG. Mean BAI ± standard deviations *(SD)* given in italics.

Condition	**No. of Plots**	**Mean BAI (m^2 ha^{-1} y^{-1})**
Increasing BA	**68**	**0.42 ± *0.41***
Falling BA	**21**	**-0.58 ± *0.52***
All Plots	**89**	**0.18 ± *0.61***

Table 2: The different components of selectively-harvested natural forests in PNG, estimated based on our analysis of the 89 PSP data for tree stems ≥10cm DBH. Only the timber volume for residual stand was estimated for tree stems ≥20cm DBH. Estimates ± standard deviations *(SD)* given in italics.

Components	**Estimate**
Mean No. of Stems $_{\geq 10cm\ dbh}$	**351 No. ha^{-1} ± *100***
Stand BA *(SBA)* $_{\geq 10cm\ dbh}$	**17.68m^{2} ha^{-1} ± *4.45***
Mean BAI *(MBAI)* $_{\geq 10cm\ dbh}$	**0.18m$_{2}$ ha^{-1} yr^{-1} ± *0.61***
Stand Vol *(SVOL)* $_{\geq 20cm\ dbh}$	**115.06m^{3} ha^{-1} ± *42.23***
Mean VOLI *(MVOLI)* $_{\geq 20cm\ dbh}$	**2.38m^{3} ha^{-1} yr^{-1} ± *7.88***
ABG forest C$_{\geq 10cm\ dbh}$	**66.24 MgC ha^{-1} ± *19.50***
Mortality for 8 burnt plots $_{\geq 10cm\ dbh}$	**16.57% yr^{-1} ± *8.61***
Shannon-Wiener Index $_{\geq 10cm\ dbh}$	**3.5 ± *0.33***

Table 3: Comparison of results of our study with similar studies carried out in other tropical regions, focusing on impact of logging on change and growth of basal area for tree stems ≥10cm DBH.

Region	Unlogged Forest Mean BA (m^2 ha^{-1})	Logged Forest Mean BA (m^2 ha^{-1})	Mean BAI after logging (m^2 ha yr^{-1})	Source
PNG	29.01	17.95	0.18	Our current study
PNG	30 - 33	10 - 20		Kingston & Nir, 1988; Oavika, 1992; Alder, 1998
Sub tropical Australia	51.5	12 - 58	0.32 – 0.75	Smith et al., 2005
North Queensland Australia	37.94 – 73.42	25.86 – 41.60		Nicholson et al., 1988
South India	39.3	34.8		Pelissier et al., 1998

Legends to Figures

Figure 1: Study sites and permanent sample plots location map.

Figure 2: (a) and (b) are trends in diameter and basal area distribution since selective timber harvesting.

Figure 3: (a) Scatter plot with regression for the 89 plots with consecutive re-measurements and (b) scatter plot with regression and error bars representing the mean values of each plot. Error bars at each data point represent standard deviation from the mean. Wider error bars, for example, 10 and 20 years since harvesting indicate higher variability in the data.

Figure 4: (a) Scatter plot with regression showing average trends in residual timber volume and (b) average trends in aboveground forest carbon for harvested forests.

Figure 5: Scatter plot with logarithmic regression generated from the model developed in Queensland rainforests (Vanclay, 1994) showing BA growth of harvested forest in PNG. The model take the form as;

$$\ln \Delta G = -3.071 + 1.094 \ln G + 0.007402\, G\, S_{h,d} - 0.2258\, G$$

Figure 6: Scatter plot with line and regression with error bars showing the average trends in MBAI since harvesting

Figure 7: Scatter plot with log linear regression generated from the model developed in the Philippines natural forests (Mendoza and Gumpal, 1987; Vanclay, 1994) showing timber yield of residual stand since logging. The model takes the form as;

$$\ln V_t = 1.34 + 0.394 \ln Go + 0.346 \ln t + 0.00275\, S_h\, t^{-1}$$

Figure 8: Mortality for the eight severely burnt plots expressed as percentage BA losses before and after fire during the 1997-1998 El Nino drought. The negative mortality rates in the plots before the 1997-1998 fire are due to ingrowth while the low mortality rates in the WIMAR02 plot before the fire is due to natural causes. After the fire, mortality rates are high as a result of trees dying and the resulting basal area losses.

Figure 9: Species diversity represented by the change in Shannon-Wiener Index since harvesting. At 0.05 level, there is no significant relationship between time since timber harvesting and the Shannon Wiener Index ($p = 0.07$).