Quantitative and Qualitative Assessment of Timber Harvesting Residues: A Case Study of a Balsa Plantation in Papua New Guinea

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Abstract

The quantity and quality of the harvesting residues in a balsa plantation located in East New Britain Province of Papua New Guinea has been evaluated in this paper. The plantation was harvested manually with chainsaw and man-power to extract the industrial wood at age six years. A standard harvesting residue assessment method was applied using line transects. The total weight of the remaining harvest residues on the site after wood extraction was 211.7 t$_{\text{GREEN}}$ ha$^{-1}$ and the major component was un-merchantable stem wood (121.3 t$_{\text{GREEN}}$ ha$^{-1}$; 57.3%). Bark was the next major component of the residue (59.3 t$_{\text{GREEN}}$ ha$^{-1}$; 28.0%). The average moisture content of the wood components recovered over the two days was determined. The average moisture content in harvesting first day was 50% while the average for the day following harvest operation was about 48%. The elemental content of the harvest residues was estimated based on published data for eucalypts in the absence of data for balsa and it showed that calcium was the largest component while phosphorous was the lowest elemental component of the harvest residues. The results indicate that the level of remaining harvest residues in this study area was relatively higher than other reported studies which reflects the combination of the log specification applied and the nature of the stem defects in balsa trees. The level of residues indicated the possibility of additional woody recovery for bioenergy.

Keywords: Balsa plantation, harvesting residues, harvesting method, nutrient level, moisture content

Introduction

Balsa (Ochroma pyramidale (Cav.ex Lam.)) is a fast growing species endemic to Central America, extending from southern Mexico to Bolivia and eastwards through most of Venezuela and throughout the Antilles (Francis, 1991). The species was introduced into Papua New Guinea (PNG) prior to 1938 with the first comprehensive introduction referred to as “Milner’s Balsawood” occurring in 1947 or 1948 (Howcroft, 2002). Since that time the species has been developed in East New Britain Province (ENBP) as an important commercial crop for wood production, local processing and export (Midgley et al. 2009). Balsa is exported from PNG and supplied into the industrial market (e.g. for use in wind turbines as a composite sandwich product) and the hobby market (e.g. for model plane making and general craft). Both markets have a high quality control, with specific wood density requirements. The trees are grown on a short rotation of approximately 5 to 6 years before harvest and processing. Balsa as a cash-crop has been adopted by smallholders in the Gazelle Peninsular of ENBP as part of their livelihood strategies and it has been incorporated into local garden systems as a strategic cash-crop diversification and supplement to cocoa production. Post-balsa-harvest
residue management by smallholders varies but can include a complete site clean-up prior to either subsequent rotations of balsa with or without an intermediate but overlapping garden crop during the early stage of the balsa crop. The impact of such management on the potential yield of the sites is of concern (Midgley et al. 2009). While comprehensive nutrient deficiency guides are available for eucalypt species (Dell et al. 2001), similar supporting materials is not available for balsa growers.

Keeves (1965) provided evidence of a second rotation decline for Pinus radiata D. Don growing in South Australia. Subsequent research resulted in management practices changing (i.e. genetics and site specific management) and an analysis of operational results indicated a 60 to 70% increase in productivity (O’Hehir and Nambiar, 2010). Such practices have been adopted across many Australian industrial plantation estates. The impact of plantation management practices on the productivity of subsequent crops has been researched for short rotation plantations and Yamada et al. (2004) stated: “There is concern about the potential decrease in productivity caused by nutrient loss by intensive and repeated harvesting. It is important to determine the nutrients removed and conserve them as much as possible to prevent productivity loss and for sustainable management of industrial plantations. Careful management of the nutrient cycle through residue retention and fertiliser application is necessary to maintain high productivity.”

The level of harvest residue on sites after industrial wood recovery depends on various parameters such as applied harvesting method, equipment, stand age, product type, silvicultural regime, species, site and stand quality. The common reasons for removing harvest residues post-harvest include reducing pest risks (e.g. bark beetle hazard), preparing the site for tree planting, harvesting biomass for energy, and reducing fire risk (Schnepf et al. 2009). However, harvest residues (leaves, needles, bark and woody debris) protect soil from excessive moisture loss, recycle nutrients for trees and other plants, add structure and organic matter to soil, reduce soil erosion, and provide food and habitat for a wide variety of wildlife.

A trial of residue management impact on nutrient stores and fluxes, and the growth of subsequent rotations of Eucalyptus globulus Labill. (O’Connell et al. 2004) concluded that the impact of harvest residue management (including complete removal) had little impact on growth for more inherently fertile sites, whereas on less fertile sites, harvest residue management could adversely impact (reduce) subsequent crop productivity. The elemental content of the different biomass components is understood for a range of species. For example, Judd (1996) presents the elemental content of foliage, branch, bark, wood and litter for eucalypts (plantations and natural forests) which can be combined with species biomass allocations to estimate the nutrient impact of different residue management strategies. Balsa-specific elemental content data has not been identified nor has a breakdown of the biomass components remaining onsite after harvest and recovery of the target logs.

A comprehensive set of studies has been conducted by the Forest Industries Research Centre in Australia since 2010 to evaluate the harvest residues for different plantations. Sixteen case study areas located in a range of plantations were assessed. The study results showed that the harvest residues in sites clearfallen by cut-to-length (CTL) at the stump harvesting method (101.7 tGREEN ha⁻¹) was higher than sites clearfallen by whole tree extraction to the roadside methods (6.1 tGREEN ha⁻¹). Subsequent recovery of a proportion of remaining harvest residues with biomass collection technologies resulted in lower weight of distributed slash on the sites harvested by the CTL method. Based on the fraction test, the largest parts of the remaining slash was for stem-wood and branches (Ghaffariyan, 2013).
ENB smallholder farmers sell their balsa to local processors as standing trees. The current balsa harvesting systems can be segmented into a 100% manual system of tree falling, cross-cutting, debarking and loading of the cut logs onto trucks for transport to the processors and a manual system incorporating skidding of the fallen stems to a central point in the stand for cross-cutting, de-barking and loading onto trucks. A key difference between the two systems is the concentration of harvest residues at the landing in the skid to roadside system compared to the more dispersed harvest residues of the 100% manual system.

The level of balsa harvest residues is a concern to smallholder growers and is often encountered in discussions with smallholders. As a first step to addressing the issue of residue management, site productivity concerns and the perception of excessive "waste" as a result of balsa harvest, the following paper details the analysis of the post-harvest residues remaining onsite for a single stand of balsa growing in the Gazelle Peninsula of ENBP. This study was conducted to address the following objectives:

- Evaluate the weight of the harvest residues for a balsa harvest site;
- Measure the share of each component of the harvest residues and moisture content of the residues to determine the harvest residue dry mass;
- Exploring the reasons for leaving the residue on harvesting site;
- Generate a high level estimate of the nutrient content of the harvest residues.

**Materials and Methods**

**The study site**

The study site was a 6 year old plantation of balsa (Figure 1) located in a PNG Balsa Limited plantation in ENB, PNG, approximately 20km south west of Kokopo near the town of Warangoi, in the Rung Creek plantation (4°28′20″S 152°10′38″E). The mean annual rainfall is approximately 2,000mm, monthly mean maximum temperature varies from 31°C in July to 32.2°C in October and mean monthly minimum temperature throughout the year is 22°C. The site was previously used for smallholder gardens and nutritional status of the site is unknown. The plantation was established at a spacing of 3 m × 3 m (1,111 stems ha⁻¹ initial stocking) and at the time of harvest, the stocking rate had reduced to 377 stems ha⁻¹. The reduction in stocking was due to natural thinning rather than management interventions.

![Figure 1. The stand of balsa prior to harvest (21/11/2013).](image)

**Stand attributes sampling**

A single 0.07 ha inventory plot was installed the day before the site was harvested with each tree individually numbered to capture individual tree data. The diameter at breast height over bark (DBHOB) of all trees in the plot was measured at 1.3m, and 5 basal areas sweeps were
conducted with a basal area factor (BAF) 2 prism wedge. The trees within the plot had a basal area of 44.6 m$^2$ ha$^{-1}$, a mean diameter at breast height (DBHOB) of 38.3 cm, a mean total height of 34.5 m and an estimated total biological volume over bark of 838.9 m$^3$ ha$^{-1}$ (Jenkin et al., 2014). Post falling, the height of each tree bole to a merchantable small end diameter (SED) of 20cm and the total height of the tree was measured. Stump height and diameter was measured and recorded.

**Harvesting operation**
A fully manual harvest system was applied. That is, the fallen stems were processed into logs where they fell. Trees were manually felled with a chainsaw, and once felled, each tree was measured and marked prior to being docked into log lengths (Figures 2 and 3). Bark was removed from each log with manual tools. The log specification applied was 1.4 m to 1.8 m lengths with minimum centre diameter >20 cm. Each log was measured and log length rounded down to the nearest 0.1 m and centre under bark diameter to the nearest 1.0 cm was recorded onto the log with a water-proof crayon. Logs with an under-bark centre diameter of between 20 – 27cm were produced, marked and tallied (and paid for), however these logs were left in the field due to market conditions with only logs of equal or greater than 27 cm centre diameter over bark recovered. Each log length and diameter within the study site was recorded on an individual tree basis. Logs were manually removed from the site and loaded onto field bins, before being loaded onto a truck fitted with a hook lift.

**Figure 2. Tree felling with chain saw**

**Figure 3. Carrying debarked logs**

**Harvesting residues assessment**
The Forest Industries Research Centre (FIRC) standard methodology for harvest residue assessments (Ghaffariyan et al. 2012a) was considered and modified to take account of the different levels and nature of harvest residues present in a post-harvest balsa coupe. The sample point plot was increased from 0.5 m × 0.5 m to 1.0 m × 1.0 m (Figure 4). The modified system was applied to estimate the onsite green weight of the harvest residues and to estimate the percentage of each residue component (as defined in Table 1) to detail the nature of the balsa residues. The post-harvest area was walked to determine the uniformity of distribution of the harvest residues. It was determined that the residues distribution pattern while variable, did not exhibit distinct strata: that is, the harvest system did not aggregate the harvest residues. The harvest residue assessment was conducted in this balsa plantation commencing in the 0.07 ha plot and extending along a ridgeline within the study site. The assessment covered a study area of approximately 1 ha along the harvested ridge and the plots were located every 10m following a straight transect. A total of 21 plots were installed: 4 plots were sampled on the 11/09/2013 and 17 plots on the 12/09/2013.
Table 3: Attributes of the residue sample components.

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bark</td>
<td>The bark of the stem of the balsa tree.</td>
</tr>
<tr>
<td>Small branches</td>
<td>Branches from the tree crown on to which the leaves were attached.</td>
</tr>
<tr>
<td>Medium Branches</td>
<td>Branches from the tree crown which were secondary to the jorquette but which did not have leaves attached.</td>
</tr>
<tr>
<td>Large branches</td>
<td>Branches from the tree resulting from the jorquette but not present as a multi-stem.</td>
</tr>
<tr>
<td>Large Butt Stem-wood</td>
<td>Stem-wood taken from within less than 2 m from the tree stump.</td>
</tr>
<tr>
<td>Small stem-wood</td>
<td>Stem-wood with an mid-stem over-bark diameter of less than 20 cm.</td>
</tr>
<tr>
<td>Leaves</td>
<td>Leaves from the crowns of the trees (which included a large petiole).</td>
</tr>
</tbody>
</table>

Within each of the 21 1 m × 1 m plots as well as weighing the total weight, all stem-wood was weighed separately, and a reason recorded why it was not recovered as a log. From the 21 plots, 10 plots were randomly selected to have the fractions weighed individually to estimate the percentage share of each fraction (Figure 5). The moisture content of the residues was measured from the collection of 7 samples taken the day of harvest and 7 samples the day following harvest. Samples were oven dried in a laboratory oven to a constant weight to determine oven dry weight.

Figure 4. Laying the 1m square plot. Figure 5. Cutting large harvest residues to weigh

The outcome of the biomass fractions analysis was converted from green to oven dry weight using the determined moisture content for the residues harvested on the same day. In the absence of specific elemental content data for balsa trees grown in PNG, a composite dataset for plantation grown eucalypts was used to calculate an estimate of the elements contained within the different residue components (see Table 2). These fractions were applied to the estimated oven dry residue components to generate a high level and indicative elemental content of the harvest residue components.
Table 4: A breakdown of the elemental content (% dry weight basis) of plantation grown eucalypts (Symphyomyrtus) species (Judd, 1996).

<table>
<thead>
<tr>
<th></th>
<th>Nitrogen (% dry weight)</th>
<th>Phosphorous (% dry weight)</th>
<th>Potassium (% dry weight)</th>
<th>Calcium (% dry weight)</th>
<th>Magnesium (% dry weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem-wood</td>
<td>0.12</td>
<td>0.005</td>
<td>0.12</td>
<td>0.10</td>
<td>0.035</td>
</tr>
<tr>
<td>Branches</td>
<td>0.40</td>
<td>0.04</td>
<td>0.35</td>
<td>0.75</td>
<td>0.15</td>
</tr>
<tr>
<td>Bark</td>
<td>0.35</td>
<td>0.04</td>
<td>0.32</td>
<td>2.40</td>
<td>0.19</td>
</tr>
<tr>
<td>Leaves</td>
<td>1.75</td>
<td>0.12</td>
<td>0.70</td>
<td>0.75</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Results

Harvesting residues
Based on the inventory data, the average weight of the harvesting residues in the study area was 211.7 tGREEN ha\(^{-1}\) (standard error= 33.5). The major component of the harvest residues was stem-wood (121.3 tGREEN ha\(^{-1}\)) which formed about 57.3% of total harvesting residues. The share of other components of harvest residues is presented in Table 3.

Table 3. Share of remaining slash components

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem-wood</td>
<td>57.3</td>
</tr>
<tr>
<td>Branches</td>
<td>14.2</td>
</tr>
<tr>
<td>Bark</td>
<td>28.0</td>
</tr>
<tr>
<td>Leaves and petioles</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The average moisture content of the wood components for two days is presented in Table 4. The average moisture content on the day of harvesting was 50% while the average for the day following harvest was about 48%. Although it had rained during the day after harvesting, due to tropical weather conditions, there was a 2% moisture loss based on the sampling results. For the harvesting day moisture content assessment, the small branches had the highest moisture content (63%) while for the day following harvest, large branches were the wettest component of the residues with moisture content of 53%. Figure 6 presents the dry weight of residues in the different plots.

Table 4. Moisture content of different wood component in two days

<table>
<thead>
<tr>
<th>Type</th>
<th>Moisture content in harvesting day (%)</th>
<th>Moisture content in day following harvesting (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bark</td>
<td>53</td>
<td>50</td>
</tr>
<tr>
<td>Small branches</td>
<td>63</td>
<td>51</td>
</tr>
</tbody>
</table>
The components of 18 residue samples were specifically analysed to determine their bark thickness, weight, length, diameter and the reason for the residue remaining onsite. These results are shown in Table 5. From the results, 22.7% of the weight of residue stem-wood was bark weight where the individual stem-wood weight averaged 11.0 kg/piece with an average length of 2.4 m and a diameter of 26.9 cm.

Table 5. Characteristics of the residue stem-wood.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Standard deviation</th>
<th>Confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net bark weight per log (kg)</td>
<td>2.5</td>
<td>2.4</td>
<td>± 1.2</td>
</tr>
<tr>
<td>Net stem-wood weight per log (kg)</td>
<td>8.5</td>
<td>10.0</td>
<td>± 5.0</td>
</tr>
<tr>
<td>Total length (m)</td>
<td>2.4</td>
<td>2.8</td>
<td>± 1.4</td>
</tr>
<tr>
<td>Diameter (cm)</td>
<td>26.9</td>
<td>6.5</td>
<td>± 3.2</td>
</tr>
<tr>
<td>Bark thickness (cm)</td>
<td>6.6</td>
<td>1.6</td>
<td>± 0.8</td>
</tr>
</tbody>
</table>
Given the importance of addressing the issue of concern as to the levels of harvest residues and a need to better understand the cause of stem-wood residues, the plot sample data was collated to determine the detailed attributes of the residues. Figure 7 indicates that the percent by weight of the bark residue component is 21.1% and the under-bark stem-wood was 78.9% of the stem-wood residue (45.4 and 169.9 \( t_{\text{GREEN}} \text{ ha}^{-1} \) respectively) (Figure 8). The attributes of each piece were measured for each sample indicating a mean bark thickness of 6.5 mm (SD=1.6 mm), a mean under-bark diameter of 26.5 (SD= 6.5 mm) and a mean length of 2.6 m (SD = 2.8 m). The cause of stem-wood rejection on a \( t_{\text{GREEN}} \text{ ha}^{-1} \) basis was collated. The two sets of analysis have been included as the rankings of the main causes of stem-wood rejection on a weight basis provides the true impact of the rejection whereas it is possible that the number of pieces creates a greater visual impact and perception. On a weight basis, butt log red heart was the main cause of rejection (31%), whereas on a number of pieces basis, stem sections with an under-bark diameter below the minimum under-bark diameter specification (< 20 cm) accounted for 47% of rejects. Stem defects (e.g. due to jorquettes) resulted in 24% by weight of the rejects but only 16% by piece numbers: the low piece number may result in a perception that this issue is of less significance. Under the current market conditions the take or pay logs (with mid log under-bark diameters of 20 to 27 cm) accounted for 13% of the rejections on a weight basis and 21% on a piece number basis.

![Figure 7. A breakdown of the bark and stem-wood on a green weight basis.](image)

![Figure 8. A summary of the cause of stem-wood rejection identified in the sample plots on an under-bark green weight basis.](image)
**Nutrient level of harvesting residues**

Based on the estimated harvest residue dry matter and the indicative plantation-grown eucalypt biomass elemental component, highly indicative elemental contents were estimated (Figures 9 and 10 present indicative elemental content of the harvest residues on a kg per hectare basis). Based on the weight of residues onsite and the indicative elemental content, the balsa bark is the most critical component with the branches and stem-wood being of similar importance. The leaves are the least significant of the harvest residue components. Calcium is the most significant element by weight, followed by nitrogen and potassium.

**Figure 9.** The elemental content of balsa harvest residues.

**Figure 10.** Total elemental content segmented by balsa harvest residue component.

**Discussion**

The total amount of harvest residue of 211.7 t\_\text{GREEN} ha\(^{-1}\) is relatively high compared to other harvesting residue studies in hardwood forests in other countries; 106.5 t\_\text{GREEN} ha\(^{-1}\) for eucalypt plantations harvested by cut-to-length (CTL) harvest method and 6.1 GMt/ha in whole tree extraction method in Western Australia (Ghaffariyan, 2013), 64.0 t\_\text{GREEN} ha\(^{-1}\) for eucalypt plantation harvested by CTL method in south-western Australia (Shammas et al. 2003) and 160 t\_\text{GREEN} ha\(^{-1}\) for hardwood stands in USA (Beardsell, 1983). Based on the data presented in Figures 7 and 8 the driver of the harvest residues is a combination of acceptable log specifications and the nature of the balsa tree e.g. the inherent defects in the stem.

Harvesting method was found to be a significant factor influencing the level of harvesting residues in Australian plantations (Ghaffariyan, 2013). The current CTL method as applied
on this site is a reflection of the internode length of the balsa stems; the length of the boards in the sawmill – around 1.4 to 1.8 m maximum; the length of the manufactured product e.g. balsa end grain blocks of approximate dimensions of 900×900×900 mm. The manual measurement and optimisation of logs from within the stem takes account of the lack of uniformity with balsa as a crop. One recent mechanisation has been to skid the full balsa stems to the roadside for processing on a landing. This accumulates the significant harvest residues at one point. If the full stems were to be taken to a landing, a significant volume of residues would result particularly if the stems were extracted with the bark on. The introduction of higher levels of mechanisation is an option but great care would be required to realistically assess this under the local circumstances.

There are no current markets for balsa harvest residues. The level of harvest residues presents an opportunity for supply as feedstock to additional industry development such as bioenergy. The moisture content of the samples is within the range of reported harvesting residues (Ghaffariyan et al. 2012b). If the future aim of the plantation management is using residues for bioenergy purposes, the residual stem-wood could be dried naturally (which would be a relatively fast process in the operating environment as shown by a 2% drop in one day in this trial) at the storage point to reduce the moisture content and increase net calorific value (Acuna et al. 2012). All fine materials such as leaves, twigs, small branches or bark and leaves can be left on the site to maintain soil fertility (Rothe, 2013). There are two key considerations: recovery of the materials and the impact on sustainability.

If market opportunities were identified for the harvest residues, the dimensions of residue logs (2.4 m length and 26.9 cm diameter) and average weight of 11 kg per log indicate the appropriate piece size for man-powered wood extraction which is currently the dominant extraction method in the region. In the case of identified markets for the harvest residue, further exploration of the efficiency of using draught animals or mechanical systems would be warranted and could build on experience from Europe (Magagnotti and Spinelli, 2011) and past studies in PNG (Pumfrey, 1983). However, the small piece size is likely to present a real challenge for any efficiency application of mechanical extraction technology as small piece size would increase the cost. Experience in other plantation operations around the world has shown when there are market opportunities for harvest residue recovery, the most efficient method tends to be to skid the full stems to a central point for processing into logs and recovering the residual materials at the same time.

The main micro nutrient of interest in ENBP is boron, however nitrogen is also a concern (Midgley et al., 2009). There is a lack of general information on the impact of the different nutrients on balsa as a crop unlike other species where comprehensive guides are available (e.g. see Dell et al. 2001). Figure 10 provided a summary of the estimated elemental content of the harvest residues and calcium was the largest component. Calcium is critical for root tip and shoot growth as it is essential for cell division and growth (Dell et al. 2001). Nitrogen was estimated as the next most significant component and it is a structural component of cell walls and a component of amino acids, amides, amines, N bases, nucleic acids, alkaloids, chlorophyll and many co-enzymes (Dell et al. 2001). Potassium was the next highest estimated component of the harvest residues. In deficient plants, protein synthesis, photosynthesis and cell extensions are impaired (Dell et al. 2001). Magnesium was estimated to be the next highest component of the harvest residues and its role is as a co-ordinated metal in chlorophyll (Dell et al. 2001). Phosphorous was the least of the elemental components of the harvest residues and it is essential for plant growth via its role in metabolic processes (Dell et al. 2001).
The actual impact of any harvest residue management will depend on the interaction between the local soils. For example, how would soil pH and absolute nutrient content affect the ability of balsa trees to access the available nutrients? The role and outcome of harvest residue management on site productivity will depend on the rate of decomposition of the harvest residues, the quantity remaining after harvest and the result of site management. The bark component of the harvest residues is the most significant in terms of quantity of the elements held but the impact of any bark management practices is unknown hence any shift to greater recovery of the logs with the bark on, needs to be viewed with caution. At the other end of the spectrum the leaves on-site hold the least quantity of nutrients but given their rapid decay onsite, the importance of the leaf component may result from a continuum of nutrient release based on the decay rates of the different components.

Conclusions

The level of balsa harvest residues is greater than for other plantation harvests, which in part validates the perception of the smallholders that there appears to be a significant level of waste. However the materials remaining are un-merchantable stem-wood (due to defects or market conditions), bark and branch materials. The level of residue is a function of the nature of balsa tree stem attributes and the specifications of the logs recovered. While this analysis has significant limitations (e.g. the key assumption that the nutrient content of plantation grown eucalypts is a proxy for balsa), it does highlight the need for caution in the method of harvest residue management to maintain site fertility. While the nutrient status of the residues has been considered, there is a need to address the nutrient removal in the wood taken from the site for processing.

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