



Long-term impacts of harvest residue management on nutrition, growth and productivity of an exotic pine plantation of sub-tropical Australia

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ABSTRACT

Residue retention is an important issue in evaluating the sustainability of production forestry. However, its long-term impacts have not been studied extensively, especially in sub-tropical environments. This study investigated the long-term impact of harvest residue retention on tree nutrition, growth and productivity of a F1 hybrid (*Pinus elliottii* var. *elliottii* × *Pinus caribaea* var. *hondurensis*) exotic pine plantation in sub-tropical Australia, under three harvest residue management regimes: (1) residue removal, RR₀; (2) single residue retention, RR₁; and (3) double residue retention, RR₂. The experiment, established in 1996, is a randomised complete block design with 4 replicates. Tree growth measurements in this study were carried out at ages 2, 4, 6, 8 and 10 years, while foliar nutrient analyses were carried out at ages 2, 4, 6 and 10 years. Litter production and litter nitrogen (N) and phosphorus (P) measurements were carried out quarterly over a 15-month period between ages 9 and 10 years. Results showed that total tree growth was still greater in residue-retained treatments compared to the RR₀ treatment. However, mean annual increments of diameter at breast height (MAID) and basal area (MAIB) declined significantly after age 4 years to about 68–78% at age 10 years. Declining foliar N and P concentrations accounted for 62% ($p < 0.05$) of the variation of growth rates after age 4 years, and foliar N and P concentrations were either marginal or below critical concentrations. In addition, litter production, and litter N and P contents were not significantly different among the treatments. This study suggests that the impact of residue retention on tree nutrition and growth rates might be limited over a longer period, and that the integration of alternative forest management practices is necessary to sustain the benefits of harvest residues until the end of the rotation.

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1. Introduction

Increased demand for plantation timber and a reduction in the land available for plantation expansion increases the importance of the adoption of sustainable production forestry practices. Retaining residues on-site following clear-cut harvesting of timber plantations is an important strategy for sustaining the productivity of subsequent rotations (Smethurst and Nambiar, 1990). Harvest residues are a source of soil organic matter (SOM) and nutrients in forest plantations (Blumfield and Xu, 2003; Mathers and Xu, 2003; Goncalves et al., 2004). Although the effect of harvest residues is not always observed (Olsson et al., 1996; Knoepp and Swank, 1997), studies on pines (Proe and Dutch, 1994; Smith et al., 2000;

Simpson et al., 2003; Tiarks et al., 2003) and eucalypts (Jones et al., 1999; Nzila et al., 2002; Mendham et al., 2003) have shown significant growth responses as a result of residue retention. A number of these studies have clearly demonstrated the direct linkage of tree growth to the nutrition effect of harvest residues (Proe et al., 1999; Nzila et al., 2002; Mendham et al., 2003; Blumfield et al., 2004).

Residue impacts on tree growth, however, may change over time (Smith et al., 2000; Simpson et al., 2003), and therefore, the extent to which residues impact on productivity needs to be determined so that alternative management practices are integrated with residue management to sustain plantation productivity. Long-term experiments are, therefore, necessary to understand the variations in tree growth over time in response to different site preparations and management regimes. While a number of studies have assessed the long-term impacts of harvest residues (Proe and Dutch, 1994; Smith et al., 2000; Tiarks et al., 2003), most of these studies were conducted in temperate regions where soil processes

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and tree growth rates are slower. Long-term studies of this nature under tropical or sub-tropical conditions, where tree growth is faster and therefore growth demand for nutrients is greater, are limited.

In sub-tropical Queensland, Australia, clear-cut harvesting of slash pine plantations generates between 30 and 46 t ha⁻¹ of residues (Simpson et al., 2003). An experiment established to assess the benefits of the residues on soil properties and plantation productivity, showed positive impacts of residue retention on soil total carbon (C), total nitrogen (N), SOM quality parameters, and tree growth in the first 6 years compared to residue removal (Mathers and Xu, 2003; Simpson et al., 2003; Chen and Xu, 2005). Foliar nutrients, however, showed no significant difference across the treatments and were all above critical concentrations.

In this study, we were interested in assessing the long-term (over 10 years) nutrition and productivity of slash pine plantations, which have an expected rotation length of 25 years. Initial studies by Simpson et al. (2003) indicated that the residue effects might be rather limited. However, other studies suggest that the nutrition effect of harvest residues may be demonstrated in the longer term (Proe and Dutch, 1994; Olsson et al., 2000; Mendham et al., 2003), probably due to the late release of nutrients from slowly decomposing residues (Smith et al., 2000; Pu et al., 2001, 2002). We therefore, hypothesised that the nutritional effect could become significant in the long term as more nutrients are released from the residues over the 10 years. We also hypothesised that C input through residue retention would result in more C fixed through foliar production and recycled as litter. Litterfall is an important source of C and nutrient fluxes to the forest floor (Pedersen and Bille-Hansen, 1999) and contributes to the overall ecosystem C balance. A long-term study by Tiarks et al. (2003) showed significantly higher total litter biomass in treatments where harvest residues were retained. Thus, the benefits of retaining harvest residues could extend to subsequent rotations in the form of litter biomass C and nutrients.

Therefore, the main objective of this study was to assess the long-term impact of residue retention on foliar nutrition, tree growth and litter C and nutrient recycling. Unlike other studies, we determined both the total growth and the periodic growth rates to assess the extent to which residue retention would impact on tree growth.

2. Materials and methods

2.1. Site description and experimental design

This study was carried out in an existing residue retention experiment established in July 1996. The details of this site, including soil physical and chemical properties had been reported previously (Mathers and Xu, 2003; Simpson et al., 2003; Chen and Xu, 2005). In brief, the site is located at Toolara State Forest (26°00'S, 152°49'E), southeast Queensland, Australia. It is generally flat, with a deep sandy soil classified as a Gleyic Acrisol according to the FAO/UNESCO classification (Mathers and Xu, 2003). The climate is humid sub-tropical with a mean annual rainfall of 1354 mm, with 56% falling in summer (Simpson et al., 2003). The July to September period is relatively dry, which may extend to November (Xu et al., 2000). The summers are hot and moist with a midsummer mean daily temperature of 24.9 °C and a relative humidity of 70%, while the winters are mild, with a midwinter mean daily temperature of 14.0 °C and a mean relative humidity of 64%. Plantation trees in this region often experience both well-watered and water-limited conditions even in a year with a wet summer season (Xu et al., 2000; Prasolova et al., 2003, 2005). In

addition, annual rainfall has been below the historic mean over the last 10 years.

The experiment is a randomised complete block design with six treatments and four blocks. Gross plots were 12 rows by 12 trees at 3 m × 3 m spacing and measurement plots were 8 rows by 8 trees (0.058 ha) (Simpson et al., 2003). This study focussed on the three harvest residue retention levels, which are: (1) no residues retained, RR₀; (2) single quantity of harvest residues retained (operational quantity), RR₁; and (3) double quantities of harvest residues retained, RR₂, created by moving residues from nil residue treatments to plots with the operational quantity of harvest residues (Simpson et al., 2003). The three treatments were each applied with 50 kg ha⁻¹ of P. The plots were planted with the F1 hybrid between slash pine (*Pinus elliottii* var. *elliottii*) and Caribbean pine (*Pinus caribaea* var. *hondurensis*), with the measurement plots planted with stock from 6 different families of the hybrid. Each family was randomly allocated a row, with a double up of 2 families per row in 2 rows to make up the 8 rows.

2.2. Tree measurements and foliar and litter production sampling

In July 2006, 10 years after establishment, diameter at breast height (DBH) (measured at 1.3 m above ground), basal area (BA) and tree height (HT) were determined from all trees within the net plots of each treatment. Growth data were obtained from past samplings for the years 1998, 2000 and 2002 (Simpson et al., 2003). Foliage was sampled from the northward facing side of the tree canopy, the side having the longest exposure to sunlight during the day (Xu et al., 1995b, 2000; Simpson et al., 2003). Fifty fascicles of the most recent, fully expanded needles (approximately 1-year old) were collected from four average trees within a treatment plot and bulked as one sample (Simpson et al., 2003). These same four trees had been sampled in the previous years, unless a tree lost its 'average tree' status. As in the previous samplings, foliar sampling was carried out in mid to late winter when tree growth was minimal and foliar nutrient concentrations were at maximum (Xu et al., 1995b; Piatek and Allen, 2000).

Litterfall was measured quarterly over 15 months from July 2005 to October 2006 from five 1.0 m² litter traps, systematically positioned in each plot. Litter from the five quadrats were bulked into one sample per plot. We also sampled two distinct layers (L and F horizons) of forest floor litter, which represented different timeframes, to determine if earlier litter N and P concentrations would show the treatment effects. The L horizon comprised of the current year, fresh, brightly brownish in colour litter needles, while the F horizon comprised of the fermenting or decomposing litter layer. These horizons were sampled from five quadrats (1.0 m²) systematically positioned in each plot. The litter horizons were sampled in only three out of the four replicates for each treatment. Assuming the lifespan of fully expanded needles is about 2 years (Wienand and Stock, 1995; Piatek and Allen, 2000), the 2005–2006 litter needles of the L horizon represented foliar production of the 2003–2004 period, while the litters in the F horizon, which appeared to be at least 1–2 years older than the L horizons, were likely to be from foliar production of year 2002 or earlier. Thus, F horizon chemical parameters were related to the growth data of 2000–2002 periods.

All foliage and litter samples were oven dried at 60 °C for at least 5 days, sorted into fruiting bodies and needles before dry weight was determined. Since litter needles comprised more than 95% of the litter biomasses, they were presented here as the total litter biomass. Sub-samples of the litter samples were ground to powder in a puck and ring mill before chemical analyses.

2.3. Chemical analyses

Foliar and litter total C and N were determined by a Eurovector 3000 elemental analyser (Milan, Italy) coupled to a GVI Isoprime mass spectrometer (Manchester, UK). Foliar and litter total P, and foliar Ca, Mg and K concentrations, were analysed following nitric/perchloric ($\text{HNO}_3/\text{HClO}_4$) acids digestion of samples (Kalra, 1998; Olsson et al., 2000). Total P was determined by the ascorbic acid method (Murphy and Riley, 1962), while foliar Ca, Mg and K concentrations were determined by flame atomic absorption spectrophotometer (FAAS) (Avanti, GBC Sigma). Foliar samples from 1998, 2000 and 2002 were also analysed along with those of 2006 for total N, P and K concentrations to determine changes in long-term nutrition. Samples of all years were digested and analysed as one batch so that they were subjected to the same analytical conditions and therefore allow valid comparisons across the years.

2.4. Periodic annual increment (PAI)

In order to follow the growth process over the 10 years, the PAI of tree growth indices were calculated over an interval of 2 years as follows: PAI = difference in total growth of two consecutive years/time (2 years).

While calculations showed that DBH, BA and HT all showed similar trends, peaking at age 4 years and declining thereafter, only the PAI of DBH (PAID) and BA (PAIB) were presented in the results to represent the growth process and to correlate with the other parameters.

2.5. Total litter N and P content

Litter N and P contents for each sampling were obtained by multiplying N and P concentrations of litters with the total litter biomass for each collection. The N and P content from each sampling over the year were added together to estimate the annual N and P recycled or transferred to the forest floor as litter biomass (Piatek and Allen, 2000).

Table 1

The cumulative basal area (BA), diameter at breast height (DBH) and tree height (HT) of the 10-year-old F1 hybrid exotic pine plantation with three harvest residue management regimes in sub-tropical Australia

Treatments	BA ($\text{m}^2 \text{ha}^{-1}$)	DBH (cm)	HT (m)
Residue removal (RR_0)	24.90 ^c	21.37 ^c	15.45 ^b
Single residue retention (RR_1)	26.53 ^b	22.00 ^b	15.73 ^{ab}
Double residue retention (RR_2)	28.31 ^a	22.86 ^a	16.00 ^a

^a Means followed by the same letter in each column are not significantly different ($p > 0.05$).

2.6. Statistical analysis

Analysis of variance (ANOVA) was carried out on tree growth data, litter production, nutrient turnover and chemical parameters of each treatment at each age. For comparisons of data at ages 2–10 years an ANOVA with repeated measures was carried out on parameters of interest. Least significant difference (LSD) analysis at $p < 0.05$ was carried out to determine significant differences between treatments. Linear regression and Pearson's correlation analyses were carried out to determine relationships between the growth indices and chemical parameters. All statistical analysis was carried out using Statistix (Version 8.0).

3. Results

3.1. Tree growth

Measurements of DBH and BA at age 10 years showed that the cumulative growth was greater in both the RR_1 and RR_2 treatments than in the RR_0 treatment (Table 1), an observation which was consistent with the early growth (Fig. 1a and b). However, the gap among the treatments appeared to be narrowing at age 10 years (Fig. 1a and b). This observation might be related to the declining periodic PAID and PAIB after age 4 years (year 2000). Although these growth indices showed significant treatment effects during the early growth, the PAID and PAIB declined substantially

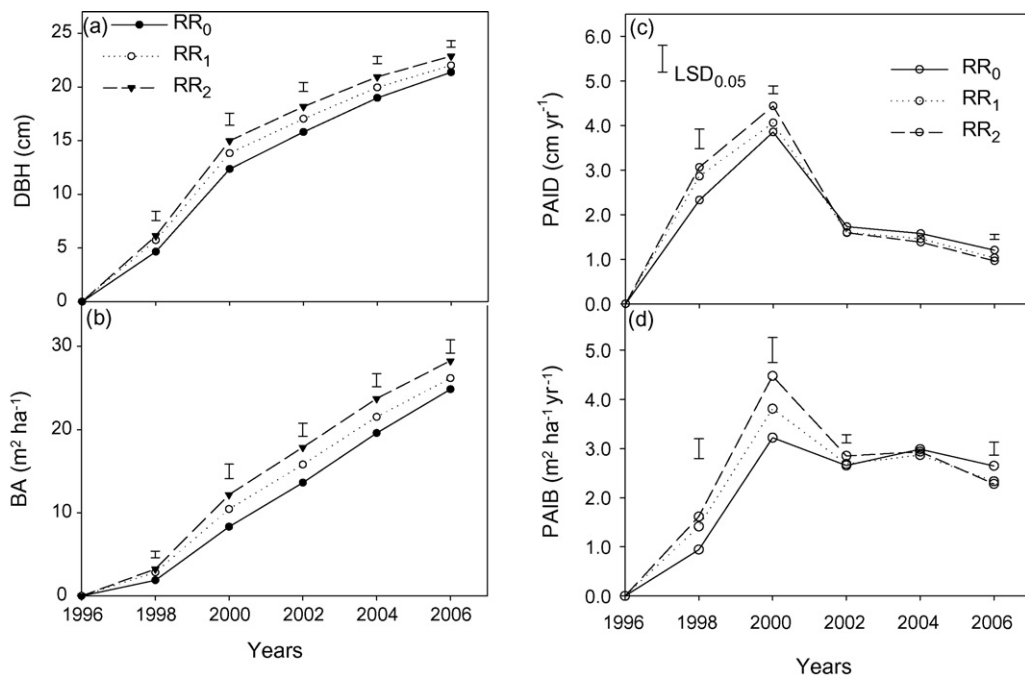


Fig. 1. The effect of different residue management treatments on the diameter at breast height (DBH) (a) and basal area (BA) (b), and the periodic mean annual increment of tree DBH (PAID) (c) and basal area (PAIB) (d) of the F1 hybrid exotic pine plantation over 10 years. The residue treatments are: (1) residue removal, RR_0 ; (2) single residue retention, RR_1 ; and (3) double residue retention, RR_2 . The bars are least significant differences (LSD) ($p < 0.05$).

Table 2
Foliar nutrient concentrations of the 10-year-old F1 hybrid exotic pine plantation under three harvest residue management regimes

Treatments	N (%)	P (%)	Ca (%)	Mg (%)	K (%)	P:N (%)	Ca:N (%)	Mg:N (%)	K:N (%)
Residue removal (RR ₀)	0.91a ^a	0.068a	0.16a	0.15a	0.34b	7.2b	17.6a	16.0a	36.6c
Single residue retention (RR ₁)	0.89a	0.073a	0.21a	0.17a	0.45a	8.5a	23.6a	19.2a	48.4b
Double residue retention (RR ₂)	0.90a	0.067a	0.16a	0.15a	0.50a	7.6b	17.9a	17.1a	58.5a

^a Means followed by the same letter in each column are not significantly different ($p > 0.05$).

($p < 0.005$) after peaking in year 2000 (Fig. 1c and d). Treatment effects also disappeared after year 2000, except for PAIB. By year 2006, the PAID had dropped by 68–78%, and both PAID and PAIB across the treatments were in the order RR₀ > RR₁ > RR₂ after the drop in growth rate, reversing the trend prior to year 2000. This trend in growth rate showed a significant time × treatment interaction ($p < 0.005$), in contrast to the total growth measurements (Fig. 1a and b), which showed no such interactions (ANOVA table not shown). Nonetheless, the relatively higher growth rates in the RR₀ at age 10 years were not large enough to offset the growth gains of the RR₁ and RR₂ treatments at this stage.

3.2. Foliar nutrient concentrations and tree growth

Foliar analyses revealed that foliar nutrient concentrations of the major nutrients ranged from 0.79 to 0.94% N, 0.058–0.082% P, 0.12–0.26% Ca, 0.11–0.19% Mg and 0.30–0.52% K. Except for K, these concentrations were not significantly different across the treatments. The nutrient ratios showed that the P:N ratio was higher in the RR₁ treatment. Nonetheless, these observations together with the Ca:N and Mg:N ratios could not explain the differences in the growth indices (Table 1) or be related to the residue management regimes. Both foliar N and P concentrations were either marginal or below critical levels (Table 2). Foliar K concentration and K:N ratios (Table 2) were significantly greater in both the RR₁ and RR₂ treatments compared to the RR₀ treatment. This observation occurred consistently over the past 10 years (Fig. 2a). In addition, a highly significant correlation between foliar K concentration and growth indices was also observed from year 2000 (age 4 years) (Table 3). This strong relationship became negative with PAID and PAIB after 2002. In addition, there was no significant relationship between foliar K concentration and tree growth in 1998 (Fig. 2), even though significant variations of tree

Table 3
Pearson's correlation of foliar K concentration with the basal area (BA), diameter at breast height (DBH), height (HT), and mean annual increments of DBH (PAID), BA (PAIB) and HT (PAIH) of the F1 hybrid exotic pine plantation

Year	DBH	BA	HT	PAID ^a	PAIB	PAIH
1998						
Foliar K	0.54 ^{ns}	0.54 ^{ns}	0.51 ^{ns}	0.54 ^{ns}	0.54 ^{ns}	0.51 ^{ns}
Foliar K:N ratio	0.62 ^{*b}	0.63 [*]	0.61 [*]	0.62 [*]	0.63 [*]	0.61 ^{ns}
2000						
Foliar K	0.82 ^{***}	0.82 ^{***}	0.63 [*]	0.88 ^{***}	0.85 ^{***}	0.30 ^{ns}
Foliar K:N ratio	0.76 ^{**}	0.76 ^{**}	0.56 ^{ns}	0.81 ^{**}	0.78 ^{**}	0.24 ^{ns}
2002						
Foliar K	0.90 ^{***}	0.89 ^{***}	0.79 ^{**}	-0.62 [*]	0.60 [*]	-0.52 ^{ns}
Foliar K:N ratio	0.70 [*]	0.69 [*]	0.59 [*]	-0.40 ^{ns}	0.60 [*]	-0.36 ^{ns}
2006						
Foliar K	0.74 ^{**}	0.76 ^{**}	0.28 ^{ns}	-0.81 ^{**}	-0.73 ^{**}	-0.69 [*]
Foliar K:N ratio	0.78 ^{**}	0.79 ^{**}	0.42 ^{ns}	-0.85 ^{***}	-0.79 ^{**}	-0.68 [*]

^a PAID and PAIB are mean periodic annual increments calculated over 2-year intervals.

^b Asterisks (*, **, and ***) indicate significance at $p < 0.05$, 0.01, and 0.001, and ns = not significant ($p > 0.05$).

growth occurred along with increasing residue-loading rates (Simpson et al., 2003).

Unlike foliar K concentration, foliar N and P concentrations over the 10 years (Fig. 2) were not significantly different among the treatments. However, both nutrients declined significantly ($p < 0.005$) after age 4 years (year 2000), with foliar P concentration about 12–39% lower in the subsequent years (Fig. 2b). Similarly, foliar N concentration declined after year 2000 and was about 22–29% lower in 2002 but increased again in 2006, although still less than those in 2000 (Fig. 2c). Both foliar P and N concentrations were either marginal or below critical values at this stage, and regression analyses showed that the decreases in PAID and PAIB were significantly related to foliar P and N concentrations (Fig. 3a and d), and together they accounted for 62% of the variations of PAI ($p < 0.05$) over the 10 years.

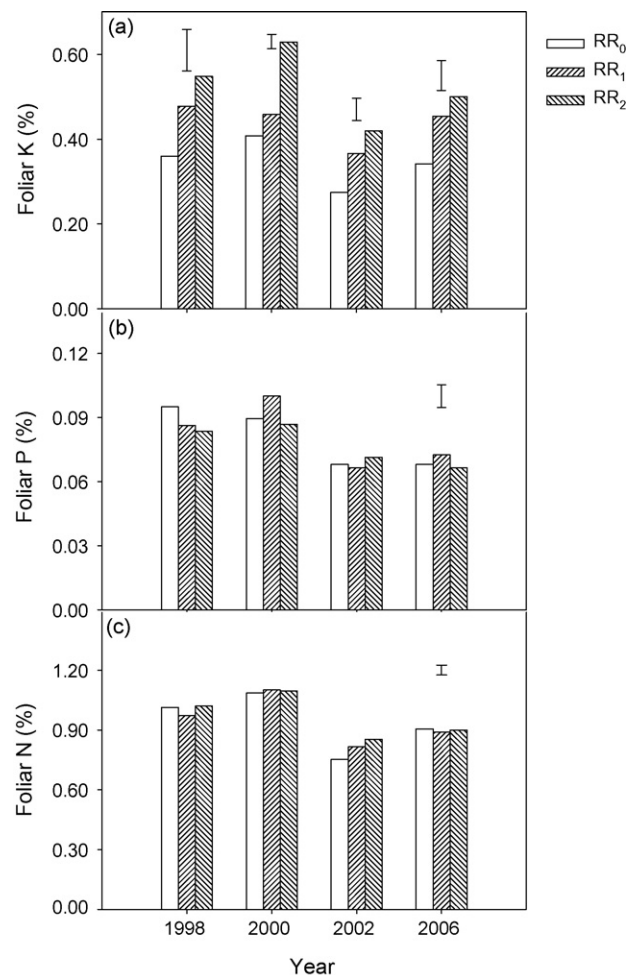


Fig. 2. Changes in foliar (a) K, (b) P and (c) N concentrations during the 10 years in the F1 hybrid exotic pine plantation under the (1) residue removal, RR₀; (2) single residue retention, RR₁; and (3) double residue retention, RR₂, treatments. The bars in (a) are the least significant differences (LSD_{0.05}) across the treatments while the single bar in (b) or (c) represent the time effect LSD_{0.05}.

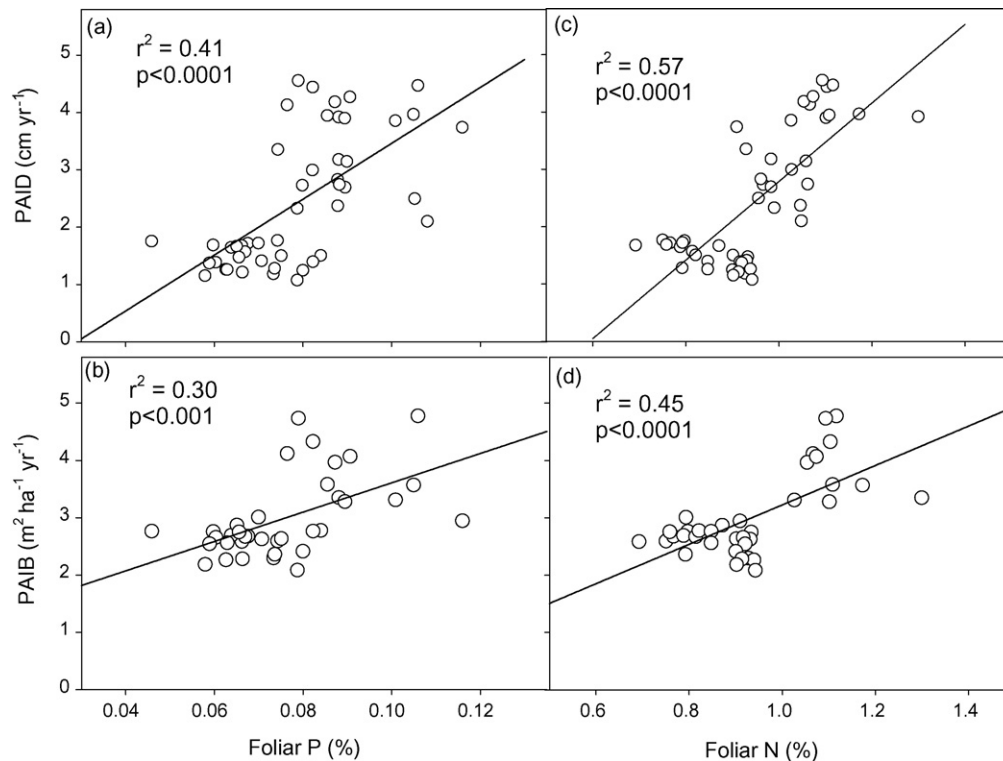


Fig. 3. The relationships between foliar P concentration and the mean annual increment of diameter at breast height (PAID) (a) and the mean annual increment of basal area (PAIB) (b), and between foliar N concentration and PAID (c) or PAIB (d) as measured after age 4 years (year 2000).

3.3. Litter production and C, N and P turnover

Fig. 4 shows the seasonal dynamics of litter production and indicates that the highest litter production occurred in the summer to autumn season. The annual litter production ranged from 1750 to 2500 kg ha⁻¹ year⁻¹. Table 4 shows that mean litter production was highest in the RR₂ treatment compared to the RR₁ treatment but not significantly different from the RR₀ treatment. Similar trends were observed for total C turnover through the litter biomass (Table 4). Total N and P turnovers were also not significantly different among the treatments.

Analysis of the forest floor litter horizons showed no differences in the N and P concentrations of the L horizon (Table 5). In contrast, the fermenting needles showed significantly higher N and P

concentrations, and lower C:N ratios, in the RR₁ and RR₂ treatments compared to the RR₀ (Table 5). Although the total litter biomass and C content were not significantly different among the treatments, total N and P turnovers were significantly higher in the RR₁ and RR₂ treatments compared to the RR₀ treatment (Table 6). Since we estimated the F horizon to be the result of foliar production in year 2002 or earlier, we correlated litter N or P concentrations with the DBH, BA and PAIB of year 2002 (Table 7). The correlations showed significant relationships between F horizon litter N and P concentrations and the DBH. The F horizon litter C:N ratio also showed a significant relationship with the DBH and BA.

4. Discussion

4.1. Tree growth

The impact of harvest residues on plantation productivity has generated great interest globally as reflected in the numerous publications on this subject. However, the long-term impacts of the residues on soil fertility and plantation productivity have not been explored extensively, probably due to the expensive task of maintaining such experiments (Corbeels et al., 2005). The present study, therefore, provided some insights into the long-term impacts of residue retention on tree growth, particularly in a sub-tropical environment. Results of this study agree with other limited long-term impact studies of harvest residues (Proe and Dutch, 1994; Smith et al., 2000; Tiarks et al., 2003) in demonstrating that the positive impact of residues on tree growth could still be observed in the long term. However, the PAID and PAIB trends indicated that the influence of residues on tree growth might be rather limited after age 4 years (Fig. 1c and d). This suggested that the current total growth observed at age 10 years mostly accumulated during the early growth phase when PAID and

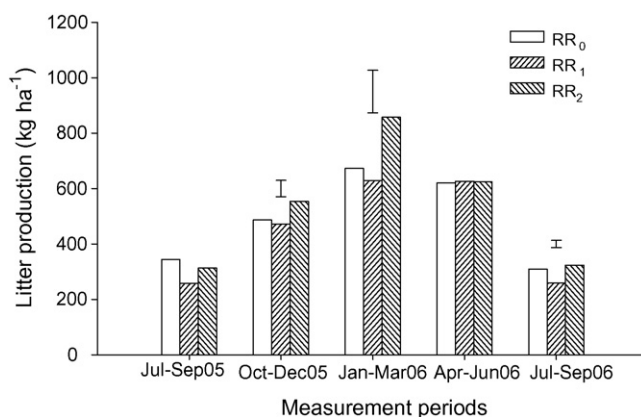


Fig. 4. Litter needle biomass production over 15 months of the F1 hybrid exotic pine in the (1) residue removal, RR₀; (2) single residue retention, RR₁; and (3) double residue retention, RR₂ treatments at age 10 years. The bars are least significant differences (LSD) ($p < 0.05$).

Table 4
Annual litter production and total C, N and P turnover of the 10-year-old F1 hybrid exotic pine plantation under the (1) residue removal, RR₀; (2) single residue retention, RR₁; and (3) double residue retention, RR₂, treatments

Treatments	Total biomass (kg ha ⁻¹ year ⁻¹)	C (kg ha ⁻¹ year ⁻¹)	N (kg ha ⁻¹ year ⁻¹)	P (kg ha ⁻¹ year ⁻¹)
RR ₀	2124ab ^a	1068ab	6.14a	0.27a
RR ₁	1984b	1006b	6.00a	0.35a
RR ₂	2348a	1177a	7.16a	0.29a

^a Means followed by the same letter in each column are not significantly different ($p > 0.05$).

PAIB were significantly higher in the RR₁ and RR₂ treatments compared to the RR₀ treatment. The significant variations of PAID and PAIB at age 10 years indicated that growth decline was more severe in the RR₁ and RR₂ treatments compared to the RR₀ treatment. Jokela and Martin (2000) reported a similar observation with the control treatments, suggesting nutrient depletion as a result of faster growth rates under alternative treatments as the main cause. However, foliar nutrient analyses at age 10 years (Table 2) did not support this view. The significant differences in growth rates, however, contributed to the narrowing of the variations of DBH and BA among the treatments at age 10 years (Fig. 1a and b). These observations suggest that integrating fertiliser (Smith et al., 2000) programs with residue retention might be useful in sustaining the long-term benefits of harvest residues on plantation productivity.

The PAID and PAIB patterns exhibited over the 10 years by the plantation were similar to those of other studies (Forrest and Ovington, 1970; Jokela and Martin, 2000). However, the peak growth increments reached at age 4 years or less in the present study, in contrast to age 8 years for slash and loblolly pines in Florida, southern USA (Jokela and Martin, 2000) and ages 5–7 years for radiata pine in south-eastern Australia (Forrest and Ovington, 1970), suggest that peak leaf area development, and therefore growth of the F1 hybrid exotic pine plantation may have occurred comparatively earlier. Declining tree growth following peak stand development has been associated with a number of factors, including nutrient limitation, hydraulic conductance limitation, increased maintenance respiration costs and biomass accumulation to the belowground growth (Gower et al., 1996; Ryan and Yoder, 1997; Jokela and Martin, 2000). The nutrient limitation hypothesis appeared to be consistent with the declining growth in the present study, irrespective of the residue management regime. This conclusion was supported by the significant positive relationship between declining PAID or PAIB and decreasing foliar N and P concentrations at ages 4–10 years (2000–2006) (Fig. 3). Available soil N and P and their foliar concentrations have been linearly correlated with the leaf area index, which increases the light use efficiency and C assimilation capacity of trees (Nambiar, 1990; Nambiar and Sands, 1993; Samuelson et al., 2004).

Table 5
Litter N and P concentrations in the L (fresh new litter approximately 1-year old) and F (fermenting litter) horizons of the 10-year-old F1 hybrid exotic pine plantation under the three harvest residue management regimes (RR₀, RR₁ and RR₂)

Treatments	N (%)	P (%)	C/N ratio
<i>L horizon</i>			
Residue removal (RR ₀)	0.37a ^a	0.026a	139a
Single residue retention (RR ₁)	0.41a	0.033a	125a
Double residue retention (RR ₂)	0.38a	0.027a	133a
<i>F horizon</i>			
Residue removal (RR ₀)	0.46c	0.028b	108a
Single residue retention (RR ₁)	0.56b	0.037a	90b
Double residue retention (RR ₂)	0.61a	0.037a	82c

^a Means in each column and horizon followed by the same letter are not significantly different ($p > 0.05$).

4.2. Foliar nutrition

In contrast to the past studies in temperate northern hemisphere (Proe and Dutch, 1994; Olsson et al., 2000), the long-term residue impacts on tree nutrition could not be observed in this study, except for foliar K concentration, at age 10 years (Fig. 2b and c). Except for P and N concentrations, foliar nutrient concentrations were above critical levels (K = 0.30%; Mg = 0.07%; and Ca = 0.12%) reported for the slash and Caribbean pines, the parent taxa of the F1 hybrid (Simpson and Osborne, 1993; Xu et al., 1995c). The element to N ratios (Table 2) were also above suggested critical levels for most tree species: K:N = 29–35%; Ca:N = 2.5% and Mg:N = 4% (Proe et al., 1999; Olsson et al., 2000; Moilanen et al., 2005). The foliar P concentrations in all treatments at age 10 years, however, were below the critical concentration of 0.093–0.11% suggested for slash pine (Xu et al., 1995a). The P:N ratio was also below the recommended ratio of 10% or more for most tree species (Proe et al., 1999). Foliar N concentration was marginal when compared to the recommended critical concentration of 0.90% for slash pine (Xu et al., 1995a). Further work is required to ascertain if these low levels of foliar N and P at age 10 years were due to depletions of N and P reserves from the residues and soil, or due to nutrient immobilisation from the residues. Nutrient competition from the current stocking density of 694 trees per hectare might also contribute to the apparent low N and P supply. A fertiliser response trial to examine the role of residues in nutrient availability is therefore necessary to confirm these possibilities.

The significant decline in foliar P and N concentrations to the deficient or marginal levels from ages 6–10 years in the present study was consistent with the concomitant decline in PAI discussed earlier. Phosphorus is the major limiting nutrient in the coastal areas of southeast Queensland (Xu et al., 1995c). However, the fact that foliar N concentration was better than foliar P concentration in explaining the variations of declining PAIs in this study (Fig. 3c and d) further supports the conclusion that N might be as important as P in these coastal sandy soils for the fast growing F1 hybrid taxon. However, unlike its parent taxa, the F1 hybrid's specific nutrient requirements have not been determined, and the current N and P application rates are based on those of the parent taxa.

Potassium has been reported to influence various processes associated with C fixation (Huber, 1984). However, the non-limiting foliar K concentrations in all the treatments over the past 10 years (Fig. 2), and the weak relationship between foliar K concentrations and growth indices in 1998 (Table 3), when significant variations in both foliar K concentration and tree growth occurred along with increasing residue-loading rates, did not support the involvement of K in increasing photosynthetic capacity as the cause of the variations in tree growth. On the other hand, the higher foliar K concentrations maintained in the RR₁ and RR₂ treatments, even though the tree growth rates decreased after year 2000, were likely due to 'luxury' uptakes of K, which were previously reported to be of greater concentrations in the soil under the residue retention treatments (Simpson et al., 2003). The higher foliar K concentrations could also be a response to water

Table 6

Total litter biomass and total C, N and P contents of the F horizon of the F1 hybrid exotic pine plantation under three harvest residue management regimes

Treatments	Biomass (kg ha ⁻¹)	C (kg ha ⁻¹)	N (kg ha ⁻¹)	P (kg ha ⁻¹)
Residue removal (RR ₀)	3443a ^a	1720a	15.90b	0.72b
Single residue retention (RR ₁)	3098a	1554a	17.40b	0.85ab
Double residue retention (RR ₂)	3963a	1977a	24.37a	1.10a

^a Means followed by the same letter in each column are not significantly different ($p > 0.05$).

stress (Xu et al., 2000; Fernandez et al., 2006), due to the drier conditions in the last 10 years at this site and the apparent demands of larger trees in the RR₁ and RR₂ treatments. Studies on other plant species showed that the maintenance of leaf pressure potential as a result of increased K during drought conditions did not always prevent the reduction in growth when other factors have more over-riding effects (Ashraf et al., 2001). This could be the case in the variations of foliar K concentrations in relation to tree growth in this study.

4.3. Litter production, C and nutrient turnovers

The lack of significant differences in the litter biomass and C turnover between the RR₀ and RR₂ treatments at age 10 (Table 4) and in the F horizon (Table 6) did not support our hypothesis that residue retention could lead to greater foliar production and therefore the amount of C recycled as litter. This finding is in contrast to the results of a 10-year-old *Pinus taeda* plantation (Tiarks et al., 2003). The lower litter production in the RR₁ treatment relative to the RR₀ and RR₂ treatments suggest that the variations in litter biomass and total C recycled across the treatments appeared to be unrelated to residue-loading rates. Other factors, such as soil moisture stress, could lead to shedding of foliage (Högberg et al., 1993; Pedersen and Bille-Hansen, 1999).

The negative relationship between the F horizon litter C:N ratio and DBH or BA of 2002 (Table 7) was consistent with the study of Smith et al. (2000) showing a significant negative relationship between forest floor C:N ratio and the DBH of *Pinus radiata*. This observation together with the significant correlations of F horizon litter N and P concentrations with the BA and DBH of 2002 (Table 7) indicates that harvest residues did affect tree N and P nutrition during the early growth of this plantation. Although the relationship between re-translocation rates in senescing needles and litter nutrient concentrations is fraught with inconsistencies (Aerts, 1996), the above evidence support the proposition that litter nutrient concentrations are reflective of tree foliar nutrient status to some extent, consistent with studies that showed a linear relationship between litter and foliar nutrient concentrations (Nambiar and Fife, 1991; Kavvasias et al., 2001). We speculate that the lack of variations in foliar N and P concentrations during early growth (Fig. 2) might be related to nutrient dilutions (Xu et al., 1995b) in the faster growing, larger biomass trees of the HR₁ and HR₂ treatments, as well as internal nutrient re-translocation to the new foliar

Table 7

Correlations between F horizon litter chemical parameters and tree diameter at breast height (DBH), basal area (BA) and mean annual increment of BA (PAIB) of 2002 (age 6 years) in the F1 hybrid exotic pine plantation

Variables	DBH	BA	PAIB
Nitrogen (N)	0.68 ^a *	0.64 ^{ns}	0.56 ^{ns}
Phosphorus (P)	0.67*	0.65 ^{ns}	0.43 ^{ns}
P × N interaction	0.71*	0.68*	0.55 ^{ns}
C:N ratio	-0.69*	-0.66*	-0.54 ^{ns}

^a Asterisk (*) indicates significance at $p < 0.05$, and ns = not significant ($p > 0.05$).

needles from the lower canopy or older, not necessarily senescing needles (Nambiar and Fife, 1991).

5. Conclusion

Harvest residue impact on tree growth could still be observed after 10 years following the establishment of the F1 hybrid exotic pine plantation. Most of this growth was accumulated in the first 4 years, after which tree growth declined significantly, most likely as a result of declining foliar N and P concentrations. Foliar N and P concentrations at age 10 years showed no treatment effects and were either marginal or deficient. On the other hand, litter N and P concentration variations suggest nutritional impact of residues during the early growth, and could be a useful indicator of tree nutritional status. The influence of residues on litter production and biomass C recycling at age 10 years is not clear at present. These findings support the conclusion that harvest residues did have a positive impact on tree growth; however, its impact appeared to be reduced at age 10 years as indicated by the periodic growth rates and the closing gap among the treatments. Whether total tree growth in the RR₀ treatment will draw level with those in the RR₁ and RR₂ treatments is not certain at this stage. Nonetheless, integrating alternative management strategies such as later age fertilisation with residue retention strategies may be necessary to ensure the benefits of residue retention sustained to the end of the rotation.

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