Growing confidence in forestry's future Research Programme

SCION FORESTS ▪ PRODUCTS ▪ INNOVATION

Date: December 2019
Reference: GCFF TN-030

Technical Note

Effects of harvest disturbance and fertiliser addition on radiata pine wood quality – results from end-of-rotation assessments in a national trial series across New Zealand.

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Summary: Data from end-of-rotation assessments at three long-term site productivity trials installed at Woodhill, Tarawera and Berwick forests were used to investigate the effects of harvesting residue removal practices during the previous rotation and repeated fertiliser addition during the current rotation on selected wood quality attributes. Growth and wood properties information was collected from almost 600 trees at these three sites and 116 trees were felled to obtain more detailed wood quality information on logs and cross-sectional discs. There was little or no effect of different levels of harvesting removal (stem only, whole tree, whole tree + forest floor) on any of the measures of wood quality. However, repeated fertiliser addition throughout the course of the rotation (up to 3200 kg N/ha at Woodhill Forest) did result in adverse impacts on wood density, stiffness, branch size and heartwood content. The degree to which these affect returns to forest growers and end-product performance will depend on the market segment that logs are being sold into. It is recommended that nutritional strategies aimed at increasing productivity should incorporate studies to evaluate their potential adverse impacts on wood quality.

Introduction

Forest harvesting practices can have an impact on site nutrient pools through removal of biomass containing nutrients and disturbance of the forest floor. The effect of harvesting depends on whether the whole tree is extracted or just the stem and the degree to which the forest floor is disturbed. To compensate for the removal of nutrients at harvest, forest managers may add fertiliser, although forest fertilisation in New Zealand is mostly undertaken to address chronic nutrient deficiencies. However, relatively little is known about the impact of harvesting disturbance on the growth of the next rotation of trees and whether any growth losses can be compensated for through fertiliser addition. This is due in part to the long-term nature of experiments required to address this question.

There is considerable interest in understanding the impacts of biomass removal and fertiliser addition on long-term site productivity both in New Zealand and internationally[1]. This is driven by the need to understand the long-term sustainability of forestry, particularly under intensified management. New Zealand is fortunate to have a series of trials that were installed between 1986 and 1994 to provide data to answer this question[2]. These trials also provide an opportunity to study the impacts of harvesting disturbance and biomass removal on aspects of wood quality.

Compared with other intensively-managed forests around the world (e.g. loblolly pine in the south eastern United States and eucalyptus in Brazil), there has been relatively few studies examining the impacts of fertiliser addition on radiata pine wood quality[3]. Most studies that have been undertaken have typically focused on the impacts of nitrogen fertiliser addition or nitrogen fertility on wood density[4–7]. These studies generally showed that there was a negative impact of nitrogen fertility or applying nitrogen fertiliser on wood density. For example, Cown and McConchie[4] found that nitrogen fertiliser applied at rates of up to 208 kg N/ha resulted in a decrease in wood density in the year following fertiliser application, but they concluded that "the effects of fertiliser addition on wood density were of little technological significance". In a study where three separate applications of biosolids (at rates of 300, 450 and 600 kg N/ha) were made to radiata pine, a small but significant reduction in wood density and acoustic, a proxy for wood stiffness, were found[7].

Wood density has been shown to be negatively correlated with both foliar nitrogen levels and soil nitrogen[5,6]. Using data from the national wood quality benchmarking study undertaken by the Wood Quality Initiative, Beets et al[6] showed that mean outerwood density at breast height was negatively related to soil carbon to nitrogen ratio. The difference in breast height outerwood density between a highly fertile site (C/N=25) and a lower fertility site (C/N=12) was estimated to be approximately 35 kg/m^3. Increasing nitrogen supply to trees growing on a low fertility site through planting lupins was shown to reduce wood density[5]. The change in wood density in each annual growth ring was correlated with nitrogen uptake by the trees as measured by foliar nitrogen concentration.

Outside of these studies there has been little investigation of the effects that different practices which potentially alter nutrient supply to trees have on wood quality. This Technical Note presents the results of a study investigating the effects of harvest residue treatment and long-term repeated fertiliser addition on wood density, stiffness, heartwood content, stem shape, bark thickness and branch size.

Method

Overview of LTSP trials
The study was undertaken at three New Zealand Long-Term Site Productivity (LTSP) trial series located at Woodhill Forest, Tarawera Forest, and Berwick Forest. Site data are summarised in Table 1. All sites were second rotation *Pinus radiata* (D. Don) planted forest which range in site fertility with low fertility at Woodhill forest and Tarawera forest and higher site fertility at Berwick. The LTSP trials each have a split-plot, randomised complete block design, with three replicates at Woodhill and four replicates each at Tarawera and Berwick. Internal measurement plots were 20 x 20 m, with 5 m wide treated buffers. Harvest residue removal treatments were applied to all sites at the beginning of the second rotation of whole-tree harvest plus forest floor removed (FF), whole-tree harvest (WT), and stem only harvest (SO). At Berwick, only the WT and SO treatments were installed and at Woodhill an additional double slash (DS) treatment was installed. Fertiliser was applied throughout the rotation using a split-plot design one with fertiliser (F) and the other with no fertiliser (NF) treatment. A high rate, particularly of nitrogen with lower amounts of phosphorus and other elements, were applied to ensure ample supply of nutrients for maximum tree growth. The high nitrogen application rate is not a common practice in New Zealand forest operations. The cumulative nitrogen and phosphorus fertiliser addition over the rotation for Woodhill was 3200 kg N ha^{-1} and 100 kg P ha^{-1}, Tarawera 1150 kg N ha^{-1} and 78 kg P ha^{-1} and for Berwick 950 kg N ha^{-1} and 50 kg P ha^{-1}. At Woodhill and Tarawera the site was planted with an initial stocking of 2500 trees per hectare and thinned to waste at age 7 and 15 years at Woodhill, and at age 5 and 11 years at Tarawera to nominally 1250 stems per hectare and nominally 625 stems per hectare, respectively. At Berwick the site was planted at 1250 stems per hectare and waste thinned at age 6 years to a nominal residual stand density of 625 stems/ha. All treatments had 100% weed control.

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Table 1: Site descriptions of the three Long-Term Site Productivity experiments sampled in this study.

Variable	Woodhill Forest	Tarawera Forest	Berwick
Latitude	36°43′S	38°13′S	46°00′S
Longitude	174°24′E	176°00′E	170°01′E
Elevation	30	90	200
MAT (°C)	14.3	14.0	10.3
Annual rainfall (mm)	1330	1820	747
Slope (degrees)	3	0	0
Soil parent material	Aeolian sand	Basaltic tephra	Loess derived from schist
NZSC [1] (USDA soil taxonomy [2])	Typic Sandy Recent (Psamment)	Tephric Recent (Orthent)	Mottled Fragic Pallic (Ustochrept)

[1] NZSC (New Zealand Soil Classification)[[8]]
[2] Soil Taxonomy[[9]]

Tree growth and wood quality assessment
Permanent growth sample plots were installed in each of the treatment plots at the three trial sites. These plots were 0.04 ha in size and all trees in them were measured at regular intervals (annually for the first ten years and every two years after that) throughout the rotation. The diameter at breast height (DBH: 1.4 m) was measured on every tree and total tree height (HT) was measured on at least 12 trees in each plot. The final tree measurement at Woodhill was in April 2013 (age 27 years), at Tarawera May/June 2015 (age 26 years), and June 2016 (age 26 years) at Berwick. In conjunction with the final tree measurement, standing tree acoustic velocity was measured on a sample of ten height trees per plot using the ST300 tool (Fibre-gen, New Zealand). Breast height outerwood cores and 5-mm-diameter

pith-to-bark cores were collected on these same trees.

Two representative trees were selected from each plot for further biomass and wood quality assessment, i.e. six in total for each treatment combination. These trees were selected based on plot mean DBH. Biomass measurements were undertaken during May-July 2014 at Woodhill, July-October 2015 at Tarawera, and April-May 2017 at Berwick. Selected trees were felled, and the stem was cross-cut where the diameter reached 10 cm. Whole-stem acoustic velocity was measured using the HM200 tool (Fibre-gen, New Zealand). The stem was then cut into a series of 4-m-long logs. The large and small-end diameters of each of these logs were measured along with the branch index (BIX) in four quadrants. The acoustic velocity of each log was measured using the HM200 tool (Fibre-gen, New Zealand). These log measurements were only carried out at the Woodhill and Tarawera Forest installations. Cross-sectional discs were sampled at heights of 0.15 m, 1.4 m and then at 4 m intervals along the stem to the top of the tree. The samples were transported to the laboratory and measured for over- and under-bark diameter, basic density, heartwood content and compression wood content. The latter two attributes were based on visual assessment. The discs have been halved, air-dried to a constant moisture content and will be scanned in the future with the DiscBot system[10] to obtain further information on intra-stem variation in key wood properties.

The pith-to-bark density cores were Soxhlet extracted with methanol to remove resin. Strips were then milled from these cores using a twin-blade sawing system, conditioned to 12% moisture content and scanned using the X-ray densitometer at Scion[11]. The average density of each ring was calculated from these densitometer profiles. The proportion of earlywood and latewood in each ring was calculated using a threshold density value of 500 kg/m^3 to define latewood.

Data analysis
The analysis focused on the stem only, whole-tree and forest floor treatments, with and without fertiliser addition. Stand development was compared across these treatments by plotting the periodic measurement data on a stand density management diagram.

Differences in standing tree acoustic velocity and outerwood density values among trees were investigated using linear mixed-effects models. Fixed effects of fertilisation treatment and harvesting removal and their interaction were included in these models along with nested random effects to account for the structure of the data which included trees sampled within plots across the three trial installations.

A similar modelling framework was used to examine differences in log acoustic velocity and BIX among treatments. An additional categorical variable (log number) was added as a fixed term in the model.

Stem shape, bark thickness and heartwood content were assessed using a variable exponent taper function[12–14]. This has the following form:

$$\frac{dib}{DIB} = X^C$$

where dib is the predicted diameter inside bark (or bark thickness or heartwood diameter) at some height up the stem, DIB is the diameter inside bark (or bark thickness or heartwood diameter) at a reference height p, $X = [1-(Z)^{0.5}]/[1-(p)^{0.5}]$, Z is the relative height h/HT and C is a function of Z and other variables. Indicator variables reflecting harvesting treatment and fertiliser addition were added to the model and their significance tested.

Whole-disc density variation was modelled as a cubic function of relative height up the stem following the same approach used to develop the national models for radiata pine and Douglas-fir wood density[15,16]. Additional terms to accounts for the effects of harvesting treatment and fertiliser addition were included in the model and their significance tested. A similar approach was used to investigate the effects of harvesting treatment and fertiliser addition on ring-level density. A non-linear function was used to model the effect of ring number from the pith on wood density. Indicator variables reflecting harvesting treatment and fertiliser addition were added to the model and their significance tested

Results

The development of the different treatment plots is shown in Figure 1. From this it is apparent that the fertilised plots at the Woodhill installation (AK1029) had a different stand development trajectory than the unfertilised plots. This was most pronounced in the FF and SO harvesting treatments and indicates that there is a higher degree of site occupancy in the fertilised plots compared with the unfertilised plots. The effect was much less apparent at the Tarawera Forest installation (FR 41) and absent at Berwick Forest (FR 127). At this installation there was much greater variation in stand development among plots, likely due to the absence of a second thinning treatment coupled with significant windthrow.

Both outerwood density (Figure 2) and standing tree acoustic velocity were highest at the Woodhill Forest installation. There was no significant effect of harvesting removal treatment on either outerwood density or standing tree acoustic velocity. There was a small, but significant effect of fertiliser addition on wood density ($p=0.03$). This effect appears most pronounced at Woodhill Forest and less so at Berwick Forest. There was no significant interaction between fertiliser addition and harvesting treatment ($p=0.51$).

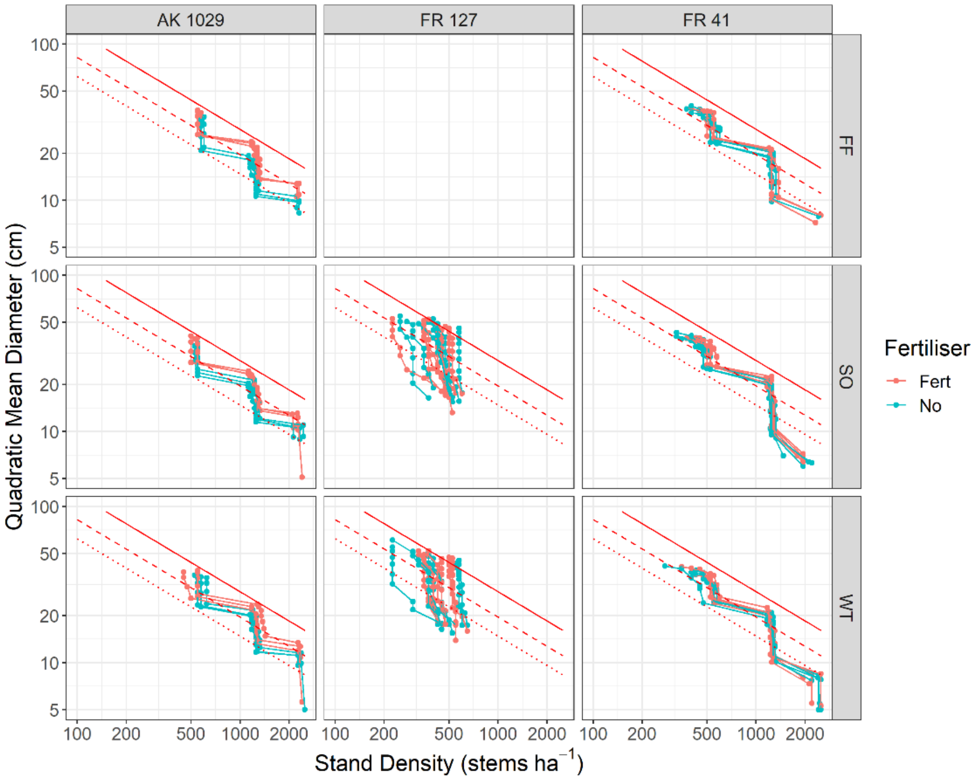

Figure 1. Stand density management diagram showing the development of the plots in the different residue treatments and fertiliser treatments at Woodhill (AK1029), Berwick (FR 127) and Tarawera (FR 41) Forests.

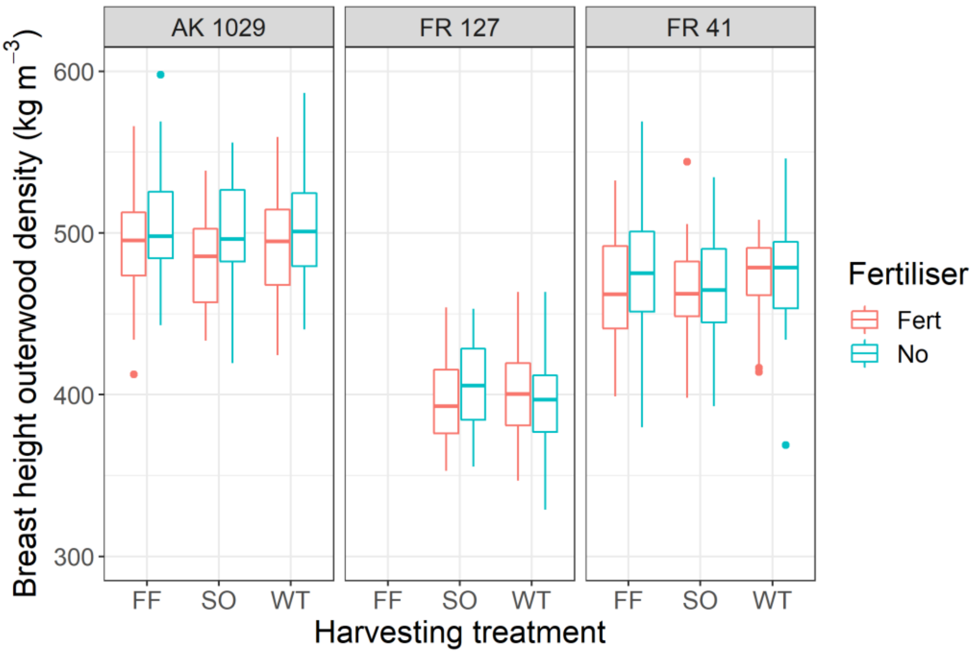

Figure 2. Comparison of breast height outerwood density among harvesting treatments with and without fertiliser addition at the Woodhill (AK 1029), Berwick (FR 127) and Tarawera (FR 41) Forest LTSP trials.

Log acoustic velocity decreased with log height up the stem (Figure 3). This decrease was less marked at the Tarawera Forest site (FR 41) compared with the Woodhill Forest (AK 1029) site. Log acoustic velocity was not measured at the Berwick Forest site. There was a significant interaction between log height and fertiliser addition, with logs sampled in fertiliser treatments having a lower acoustic velocity (p=0.005). This effect was most pronounced in the stem only treatment at Tarawera Forests, however there was no significant interaction between fertiliser treatment and harvesting removal treatment.

Branch index increased with increasing log height up the stem at Woodhill Forest (Figure 4). There was no effect of harvesting removal treatment on BIX, however fertiliser addition resulted in a significant increase in BIX across all harvesting removal treatments (p=0.037).

There were small differences in stem shape among harvesting removal treatments and with the addition of fertiliser (Figure 5). There was greater consistency in stem shape among trees sampled at Woodhill Forest compared with those sampled at Tarawera Forest. Trees sampled in the fertilised plots in stem only harvesting removal treatment had significantly different stem form with lower relative diameter at the same relative height up the stem than in the unfertilised plots particularly for Tarawera and Berwick Forests.

Bark thickness decreased rapidly from approximately 60 mm at the bottom of the stem to approximately 20 mm at 10% of total stem height (Figure 6). After this height, the decrease in bark thickness with increasing relative height up the stem was much less. The variable exponent model was able to explain 86% of the variation in bark thickness. The indicator variables for forest floor removal and fertiliser were significant (p<0.05) and there was suggestive, but inconclusive evidence that the stem only harvesting affected bark thickness (p=0.051).

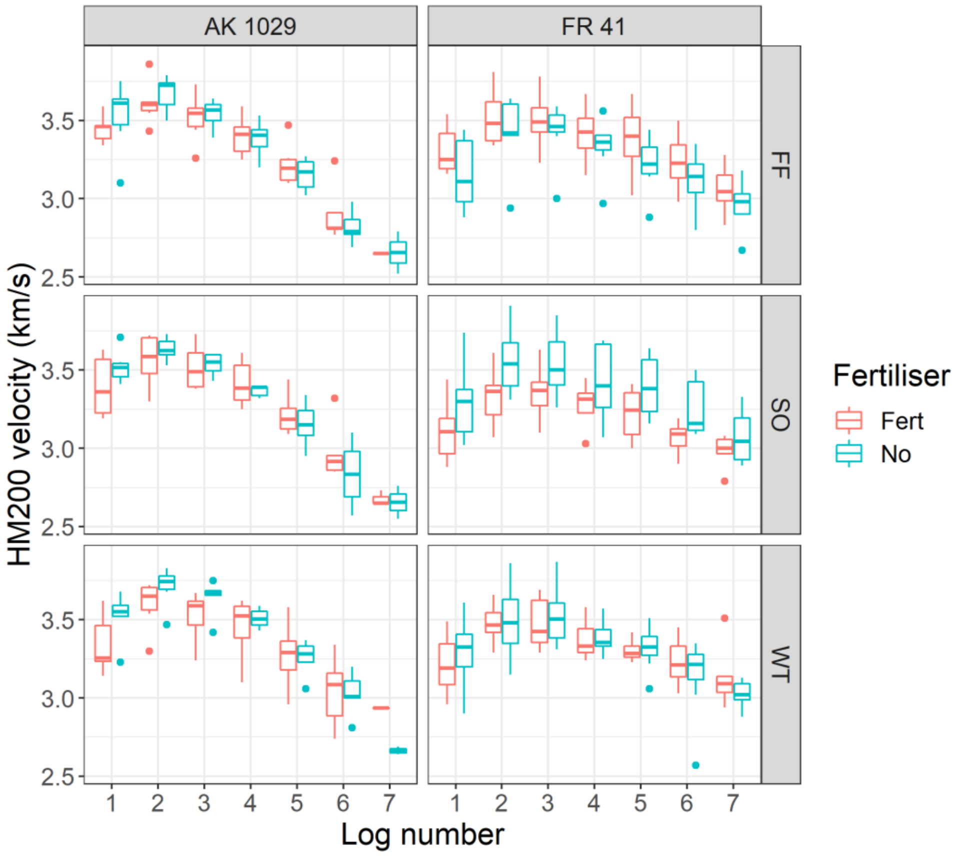

Figure 3. Effect of log height class, harvesting removal treatment (whole-tree removal, stem-only removal, whole-tree + forest floor) and fertiliser addition on acoustic velocity measured with the HM200 tool at Woodhill (AK 1029) and Tarawera (FR 41) Forests.

Disc average density decreased with increasing relative height up the stem (Figure 7). There was a large amount of variation in wood density among trees. As a result, no significant effects of fertiliser treatment (p=0.46) or harvesting residue removal treatment (p=0.13) were observed.

Heartwood content was approximately 40-50% at the base of the stem and increased slightly with increasing height up the stem (Figure 8). Beyond a relative height of 0.5 it decreased rapidly and there was generally no heartwood recorded in discs taken from the uppermost part of the stem. The variable exponent model was able to explain approximately

50% of the variation in heartwood content. The indicator variable for fertiliser addition was significant (p=0.04). This effect of fertiliser addition was particularly apparent at Woodhill Forest where trees in the plots where the forest floor had been removed when the previous stand was harvested had 10-15% greater heartwood content in the lower half of the stem. Compression wood content in the discs varied from 0% (no visible compression wood) up to 40% in the most affected discs. There was no apparent trend with height up the tree or with fertiliser addition and harvest removal treatment.

The pith-to-bark variation in ring-level wood density could be adequately modelled using a non-linear function based on ring number from the pith (Figure 9). This model explained around 39% of the variation in ring-level wood density based on the fixed effects of ring number from the pith, fertiliser addition and harvesting treatment. Both harvesting treatment and fertiliser addition were significant in the model, but the magnitude of these effects was small. Wood density was lower in the trees that had received added fertiliser, but this effect reduced in magnitude with tree age. A similar trend was observed in trees growing in plots that had received a stem only harvesting treatment. Ring-level density was slightly lower in these trees compared with those growing in plots that had received a whole tree removal or forest floor removal treatment.

Discussion

This study investigated the effects of relatively extreme ranges of harvesting disturbance and fertiliser addition treatments on selected wood quality attributes. These treatments likely encompass the full range of treatments encountered in operational practice. For example, the most extreme fertiliser addition treatments at Woodhill Forest applied a cumulative total of 3200 kg N/ha during the course of the rotation, which greater exceeds typical operational fertiliser applications which often involve a single application of 250 kg N/ha. Likewise, harvesting practices aim to retain residues on site and to minimise disturbance of the forest floor by replacing techniques such as root raking and v-blading with line raking and spot cultivation.

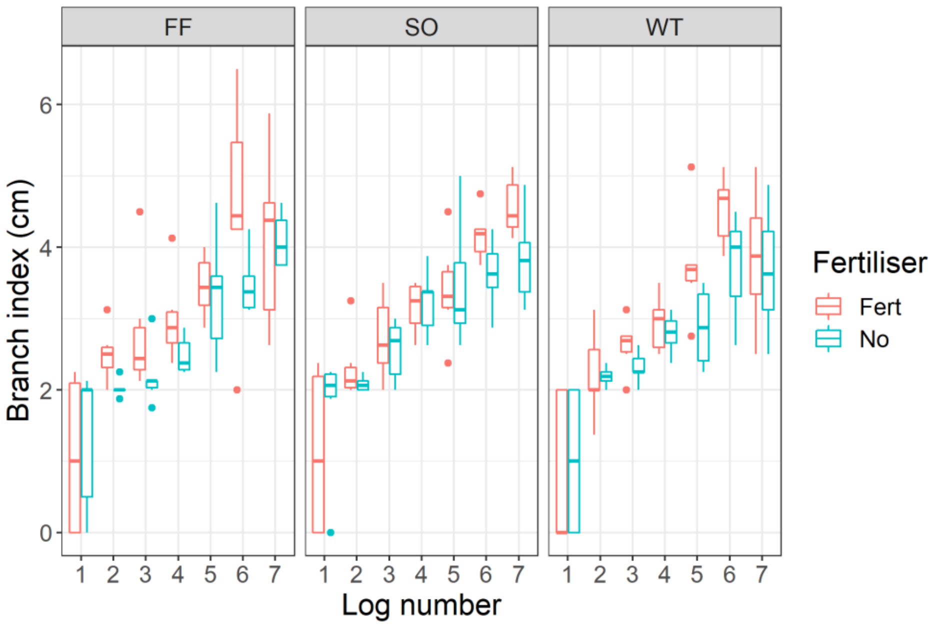

Figure 4. Effect of harvesting removal treatment and fertiliser addition on branch index of logs cut from trees at Woodhill Forest

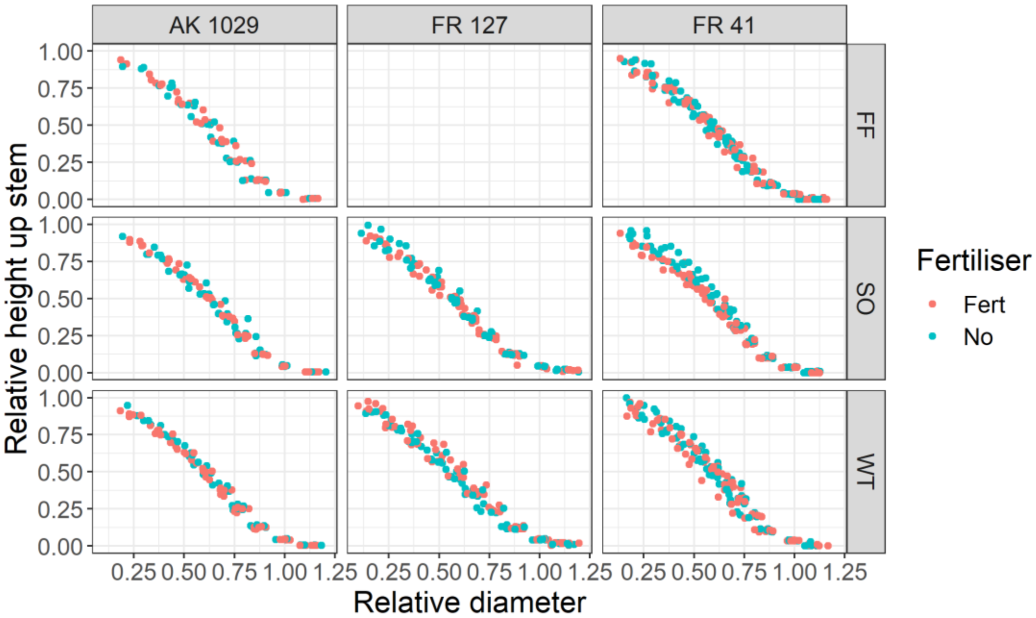

Figure 5. Comparison of stem shape among trees from different harvesting removal treatments with and without applied nutrients at three LTSP trials

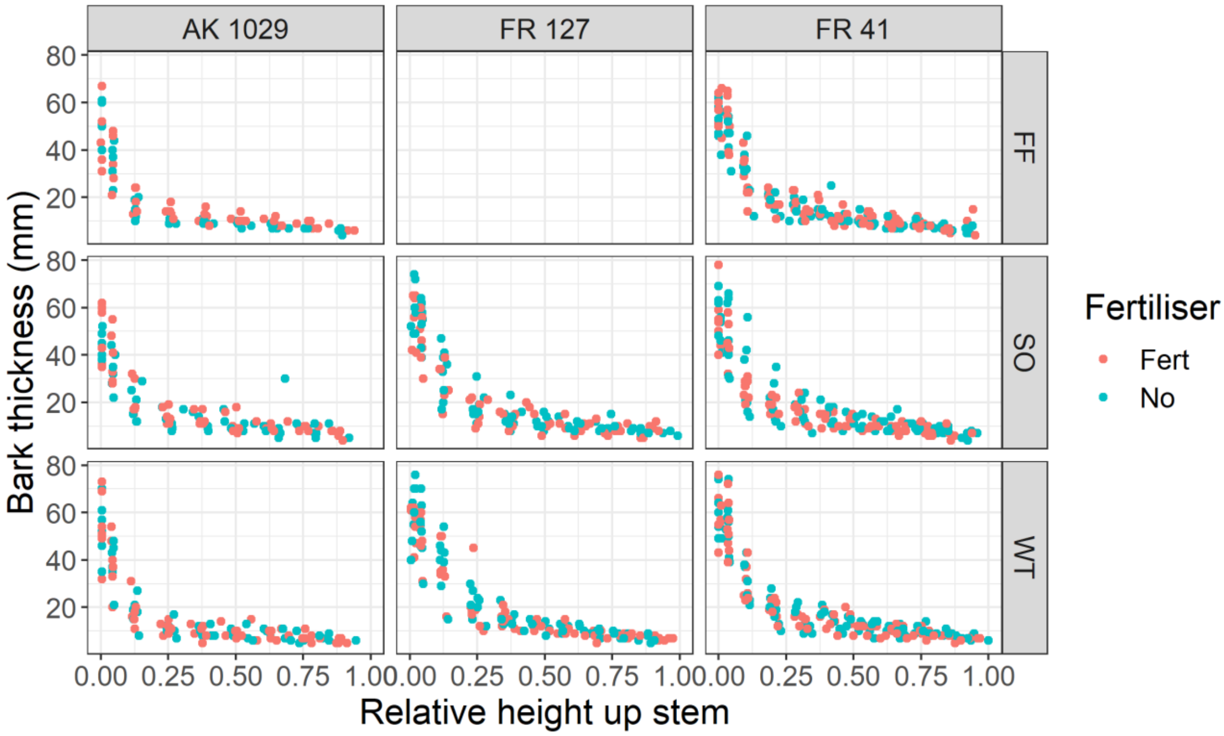

Figure 6. Profiles of bark thickness with relative height up the stem for trees sampled in plots with different levels of harvesting disturbance and applied nutrients in Woodhill (AK 1029), Tarawera (FR 41) and Berwick (FR 127) Forests.

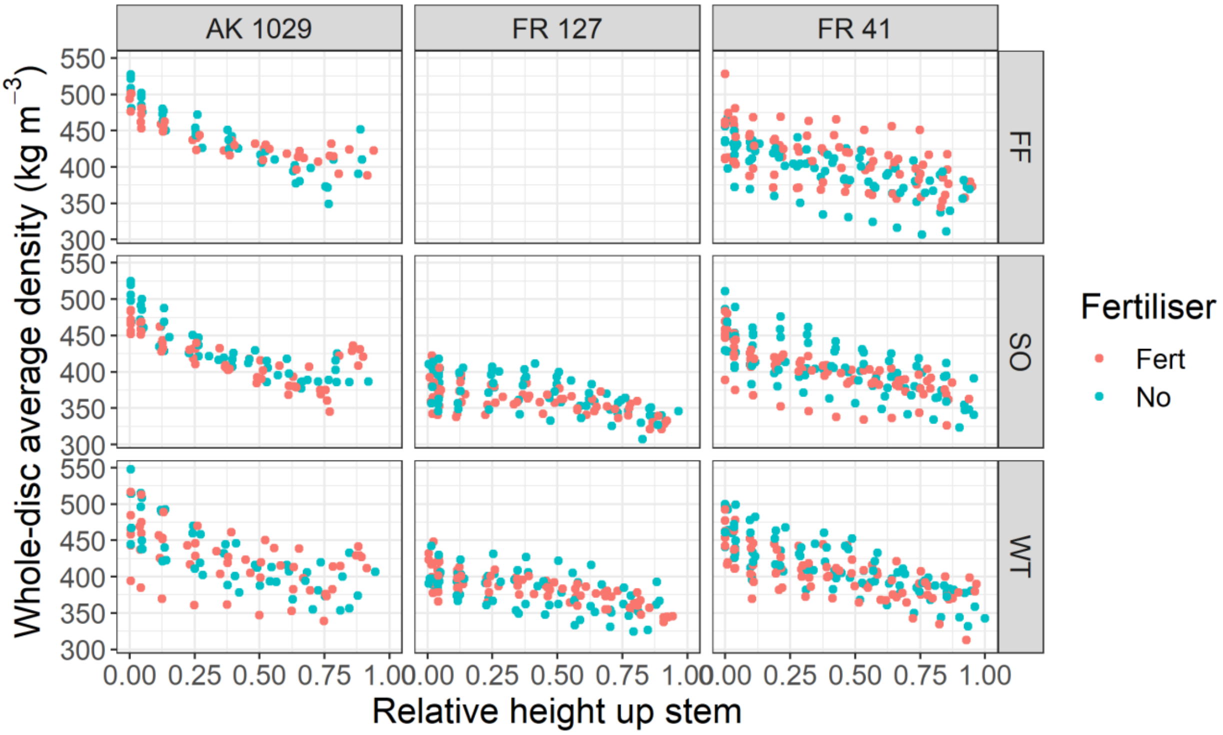

Figure 7. Profiles of whole-disc average density with relative height up the stem for trees sampled in plots with different levels of harvesting disturbance and applied nutrients in Woodhill (AK 1029), Tarawera (FR 41) and Berwick (FR 127) Forests.

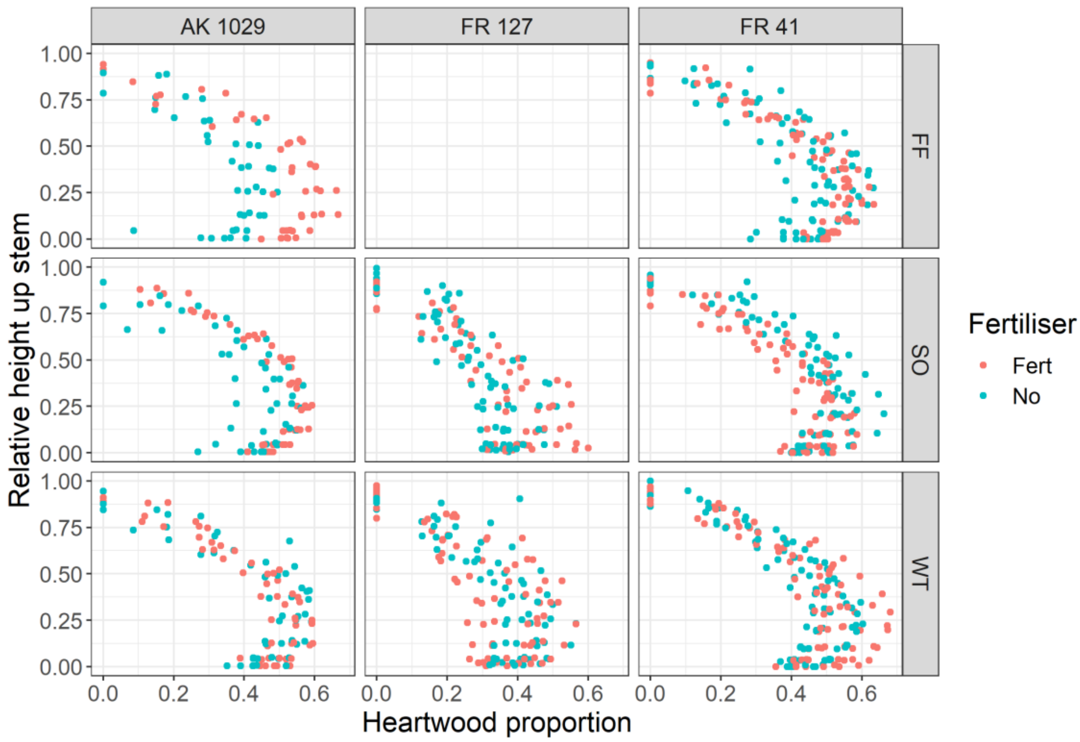

Figure 8. Profiles of heartwood proportion with relative height up the stem for trees sampled in plots with different levels of harvesting disturbance and applied nutrients in Woodhill (AK 1029), Tarawera (FR 41) and Berwick (FR 127) Forests.

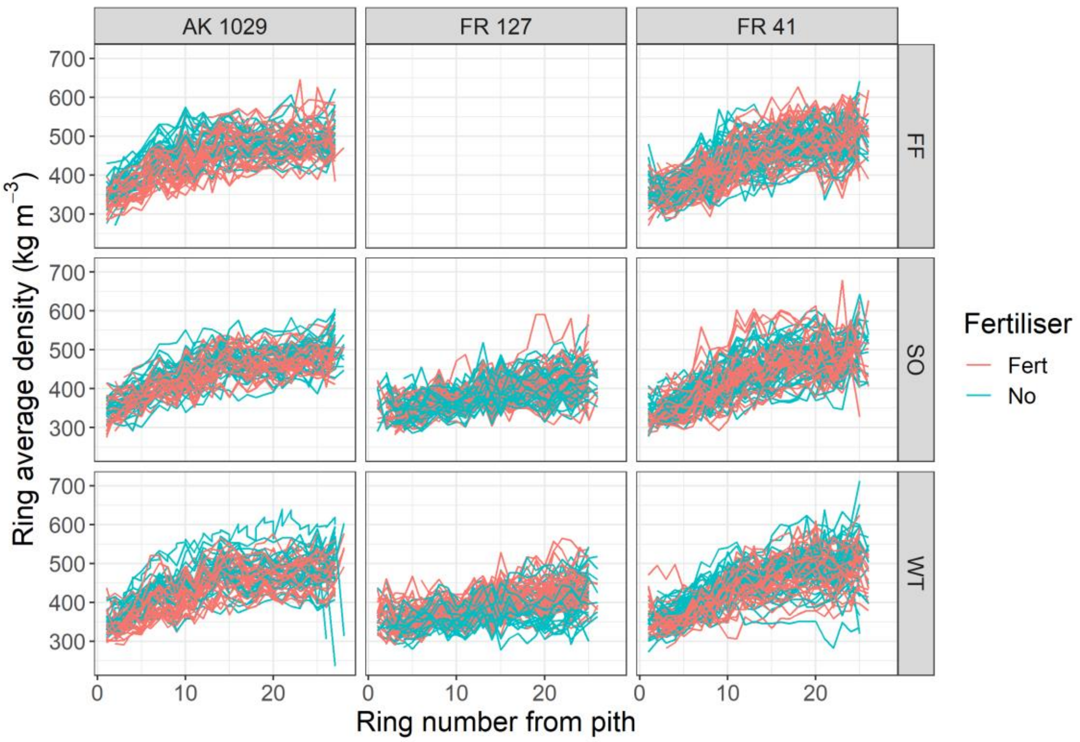

Figure 9. Radial profiles ring average density for trees sampled in plots with different levels of harvesting disturbance and applied nutrients in Woodhill (AK 1029), Tarawera (FR 41) and Berwick (FR 127) Forests.

Despite the extreme nature of some of the treatments applied in this study, their impact on growth was relatively small, with the exception of the low fertility site at Woodhill Forest where removal of whole tree and the forest floor at the time of harvest had a negative impact on stand development over the next rotation. This result confirms previously reported age 5 year and end of rotation productivity treatment impacts at the Woodhill LTSP site[2]. The Woodhill forest ecosystem nutrient stocks are low and the forest floor removal harvest treatment removed 41% of the nitrogen stocks at the site and affected the soil microbial community[17].

Given the previous history of growth responses at the Woodhill Forest site it was the most intensively measured in the wood quality study reported here. Harvest practices and fertiliser addition were found to have a statistically significant effect on many of the aspects of wood quality that were examined. Fertiliser addition resulted in an increase in maximum branch size which is consistent with previous research that showed an increase in branch size with the addition of nitrogen in 6-year-old radiata pine trees[18]. Despite the statistical significance of this result, the actual magnitude of the change was less than 1 cm. The technical significance of this result will depend on the market requirements for the grades that logs are targeting and how close the existing branch size is to the limit for these grades. The potential impacts on export log grades with their more liberal requirements around branch size are likely to be much less than those for domestic structural grades which have tighter requirements.

Log acoustic velocity was lower in the plots that had received fertiliser at both Woodhill and Tarawera Forests. This effect was most noticeable in the stem only harvest plots in Tarawera Forest. This result has potential implications for structural timber producers who require logs with adequate stiffness in order to ensure acceptable levels of structural timber grade outturn. However, it should be noted that log acoustic velocity was only measured on six trees from each treatment, so there is the potential for the result to be influenced by one exceptionally high or low stiffness tree. Standing tree acoustic measurements made on a much larger sample size (>30 trees per treatment) did not indicate any significant effect of fertiliser addition, although it should be noted that the correlation between these measurements and structural timber properties is generally poorer than that observed with acoustic velocity measured on logs with a resonance-based instrument[19].

The reasons for the increased heartwood content in trees that had received fertiliser addition are not known. In general, while the chemical and anatomical characteristics of heartwood are known along with the process through which it forms, much less is known about environmental and silvicultural factors that may affect it[20]. It has been suggested that factors that increase growth such as thinning may increase extractives content of heartwood[21], but less is known about the effect on the extent of heartwood. From a processing perspective, heartwood is generally undesirable in radiata pine as it is non-durable and causes issues for drying and treatment of lumber[22]. In pruned logs, if the heartwood diameter exceeds the defect core defined by the extent of pruned branch stubs, then the heartwood boundary defines the new extent of the defect core.

Overall, this study has provided important new knowledge on the potential impacts that harvesting practices and fertiliser addition may have on wood properties. However, it was not without its limitations. Buffer widths were small in the trial deign (5 m) and did result in nutrient transfer across treatment boundaries. Therefore, it is acknowledged that the results of intensification treatments may be under-represented. The other limitation was the small number of trees that were felled and intensively measured. Again, this could have limited the range of responses to a particular treatment that were observed. In wood quality studies, a minimum of 10-15 trees per treatment or site have typically been assessed rather than the six that were sampled here.

We recommend that additional studies should be undertaken to assess the potential impacts that any nutrition treatments designed to boost forest productivity have on wood quality. This is critical to ensure that the implications of any future intensification strategies on wood quality are understood.

Conclusions

Based on the results of long-term trials we found that harvesting disturbance has little discernible impact on wood quality in the subsequent rotation. However, fertiliser addition, particularly nitrogen may have adverse impacts on wood density, stiffness, branch size and heartwood content. The degree to which these affect returns to forest growers and end product performance will depend on the market segment that logs are being sold into.

Acknowledgements

Funding for this research came from the “Growing Confidence in Forestry’s Future” research programme (C04X1306), which is jointly funded by the Ministry of Business Information and Employment (MBIE) and the Forest Growers Levy Trust, with the support of the NZ Forest Owners Association (FOA) and the NZ Farm Forestry Association (FFA).

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