Can Nursery Application of *Trichoderma* Inoculants Improve Stand Uniformity?

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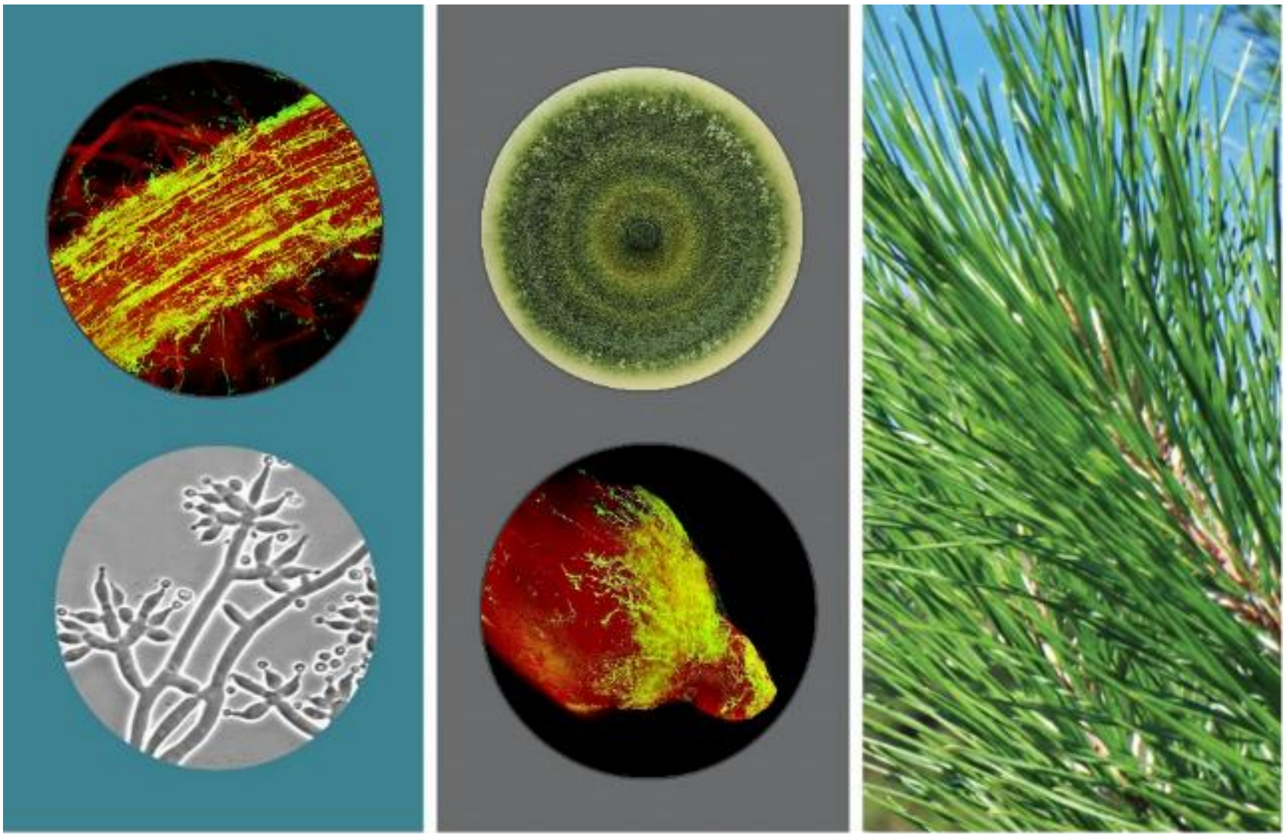

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EXECUTIVE SUMMARY

Practical methods to improve tree structure uniformity are important to forestry managers when the goal is to develop, manage and harvest a forest with low levels of variability in tree height and trunk diameter. The ability of nursery seed coat *Trichoderma* inoculants to increase the uniformity of these traits was tested using year four data from eight large-scale radiata pine trials in four important New Zealand forestry regions. The coefficient of variation (CV) and the Lorenz Curve and Gini Coefficient (GC) statistics, based on height, diameter at breast height (DBH), trunk basal area and volume, were used to quantify tree variability.

One or both *Trichoderma* treatments (PR6 and PR3a mixtures) had significantly (P<0.05) reduced CV and GC statistics in three of the eight trials compared to the control and indicated less variability was present in tree height and DBH. When meaned over all sites, CV for height and DBH in the *Trichoderma* treatments were significantly lower (by 11.8 to 13.9%) compared to the untreated control. *Trichoderma* treatments also had significantly (P<0.05) reduced CV (10.6 to 13.9%) and GC (9.2 to 11.4%) statistics when height and DBH data were used to calculate trunk basal area and volume, compared to the control. *Trichoderma* treatments PR6 and PR3a had similar levels of reduced tree variability, and both were recommended as suitable silviculture tools for reducing structure variability.

Overall, GC statistic was recommended for quantification of the effect of *Trichoderma* inoculation on tree size uniformity because it was a robust, concise and efficient indicator directly related to size hierarchy and therefore a good indicator of asymmetric competition between trees. A very close correlation between GC and CV statistics was found, therefore CV could also be used if a quick analysis is required from inventory plot or airborne laser scan data.

Nursery application of these *Trichoderma* inoculants to tree stock offers an opportunity for forest companies with either intensive or extensive silviculture practices to reduce the economic cost of stand and harvest management by increasing tree uniformity. An additional benefit to foresters of *Trichoderma* is the promotion of tree growth and increased stand productivity, as found in these and other trials established in this research programme. Future study of these trials would confirm whether this technique can continue to reduce variability in tree structure as they mature or be beneficial in other environmental growing conditions.

INTRODUCTION

Stand uniformity is a desired trait in many radiata pine timber production systems in New Zealand. Variability in plantation stands may alter the growth of individual trees and decrease productivity due to an unequal division of resources amongst competing plants (Bourdier et al. 2016, Forrester 2019). Stand uniformity and tree productivity may be increased with the planting of improved genetic stock and intensive silvicultural practices such as site preparation, weed control and fertilisation (Allen et al. 2005). In this research programme the application of *Trichoderma* inoculants to radiata pine nursery stock significantly improved growth once planted in the plantation (Whelan 2019, 2021 and 2023). Stand uniformity could also be improved by using nursery applied *Trichoderma* inoculants via seeds but this has not been studied. If this technique is successful, improvements to thinning and harvest criteria could be made leading to a reduction in production costs.

A basic summary of stand structural properties should include a measure of average or dominant tree size, plus another for density or canopy cover, and a descriptor of variation in the distribution of tree sizes (Knox et al. 1989). Numerous summary statistics have been used to describe and quantify the variability of tree sizes in plantation stands. Common methods that measure the spread of values in a dataset include the standard deviation and the coefficient of variation (CV). The standard deviation is a way to measure how far the average value lies from the mean and the coefficient of variation is the ratio between the standard deviation and the mean. The higher the coefficient of variation, the higher the standard deviation of a sample relative to the mean. The standard deviation is most used to define the spread of values in a single dataset, while the coefficient of variation is used to compare the variation between datasets of different means. In this study, the CV was chosen instead of the standard deviation because of the variation in mean growth variables both within and among trials (see Table 1).

The Lorenz Curve and Gini Coefficient statistical method, hereafter referred to as GC, was originally designed for studying income inequality but has increasingly been applied to compare the structural variability of stands in forestry studies (eg. Leite et al. 2021). When applied to tree assemblages, GC quantifies the relative inequality in size among trees growing in proximity, as a proxy of competition for the available resources (Weiner 1990). It can also be used to compare between-stand variability at stand or forest levels, or changes over time (Lundqvist 1994).

GC can be used to measure stand uniformity as a derivation from a perfectly uniform population for a given growth trait (Katholnig 2012). In brief, the trees within a plot are sorted in ascending order for the response variable of interest (eg. tree diameter at breast height). Then, the cumulative proportion of this variable is plotted against the cumulative proportion of the trees, which generates the Lorenz curve (Katholnig 2012; see Appendix A). The GC is calculated as the ratio of the area that lies between the line of equality (the one-to-one line) and the Lorenz curve, divided by the total area under the line of equality. This process can be summarized using the following formula:

$$GC = \frac{\sum_{j=1}^{n}(2j-1-n)ba_j}{\sum_{j=1}^{n} ba_j(n-1)} \tag{1}$$

where j is tree rank in ascending order from 1 to n, n is the total number of trees in a plot, and baj is basal area (m^2) (or volume, m^3) of the tree with rank j.

Perfect stand uniformity (where all trees have equal size) would have a value of 0 whereas the lowest stand uniformity would have a value of 1. However, in practice its maximum value in forest stands may reach up to 0.8 (Keren et al. 2020). An example of the calculation of the GC for two plots with the same mean DBH of 10.0cm but different levels of uniformity is presented in Appendix A.

Lexerød and Eid (2006) and Valbuena et al. (2012) compared the reliability of indicators describing forest structure based on diameter distributions and found the GC was the most suitable option for the following reasons:

- independence of scale (Weiner and Solbrig 1984) that allows comparison of tree populations that differ in their mean or dominant tree size (Valbuena et al. 2012)
- independence of sample size and allows comparison of stands with different densities or canopy cover
- low sensitivity to the number of trees in a sampling plot (Weiner and Solbrig 1984, Bourdier et al. 2016)
- is a measurement of size inequality, rather than the presence of skewness or kurtosis (Weiner and Solbrig 1984)
- is more directly related to size hierarchy and thus a better proxy to asymmetric competition between trees (Forrester 2019)
- requires no arbitrary classified diameter classes
- is spatially inexplicit, and
- has the advantage of providing a simple and concise indicator for the plot that can be used to rank forest stands according to their structural complexity.

Application of *Trichoderma* inoculants to nursery stock may be a useful tool for reducing variation in plantation tree size, but this has not been assessed in research trials. The objective of this study was to determine the effect of nursery seed coat *Trichoderma* inoculation on radiata pine tree size uniformity once established in the plantation.

METHODS

Radiata pine trees in eight plantation trials (Whelan, 2019) were measured and data used to assess forest uniformity at the sampling plot level using CV and the Gini coefficient (GC). In brief, the trials were established in 2018 in four important forestry regions (Gisborne, Northland, Bay of Plenty/Waikato and Nelson) using a randomised complete block design with 7 to 10 replications. Two *Trichoderma* treatments (PR6 and PR3a mixtures) were applied as part of a seed coat recipe to a single radiata pine seed lot and the seedlings grown under standard containerised tray management practices in a commercial nursery. Treated and untreated (control) seedlings were then planted in the commercial plantation forests that had different site preparation methods and tree densities (ranging from 800 to 1190 stems per hectare). Herbicide management was also variable in the first two years of growth, but no insecticides or fungicides were applied. Plots contained 81 trees in a 9 x 9 grid pattern. Tree height, DBH and foliar disease (percentage incidence and severity; method according to Whelan 2019) were measured in the central 25 plants four years after trial establishment. Survival was generally very high across all treatments and sites (Table 1) providing fully stocked plots for evaluating the effects of treatments on tree uniformity.

CVs were calculated using the average and sample standard deviation functions in the Microsoft 365 Excel program. GCs were hand-calculated in the Microsoft 365 Excel program. Data were analysed for significance by analysis of variance (ANOVA) and the Fisher's unprotected least significant difference (LSD) test at the 5% level using Genstat, v21 (Genstat 2021). The correlation between CV and GC for the basal area and volume variables was determined using the Pearson correlation coefficient and significance was tested with the t-test. Simple linear regression analysis of the relationship between disease severity and GC volume was also performed.

RESULTS AND DISCUSSION

An important benefit of these *Trichoderma* inoculants was the promotion of growth measured four years after the establishment of the plantations (Table 1). At all sites, both mixtures increased tree height and DBH by 6.8 and 7.7%, and the resultant plot volume calculation was increased by 13.0 and 14.6% for the PR6 and PR3a mixtures respectively, compared to the control. The ability of *Trichoderma* to promote growth, in combination with reduced stem variability will contribute to gains in economic returns for foresters.

At each site, the CV for height (ranged from 10.9 to 25.9%) was lower than for DBH (ranged from 14.6 to 38.9%) indicating less variability was present in the height data (Table 2). CV increased sharply when the calculations involved one or more variables or more complex steps, and therefore additional ways to introduce variability to the results. CV for basal area had an exponential treatment of DBH and resulted in mean values at least double (ranged from 27.5 to 67.2%) that of CV for height or DBH (Table 2). Similarly, CV volume which had an additional step of multiplication of the height variable, increased values to a range of 31.8 to 69.1%. The only exception was in the Nelson Berrymans trial where the inclusion of the height variable in the CV volume calculation lowered the values from a range of 56.3 to 67.2% to a range of 50.7 to 61.2%, due to height having proportionately lower variability than the DBH values. When meaned over all sites, CV values progressively increased as height (16.9 to 19.2%), DBH (24.3 to 28.0%), basal area (44.9 to 50.8%) and volume (47.3 to 53.0%) were considered (Table 2).

A similar pattern to CV was observed in GC for basal area and volume. At each site, the GC for basal area ranged from 15.5% to 35.7% (mean of 24.2 to 27.3% in all trials), whilst GC for volume ranged from 17.9% to 37.9% (mean of 25.4 to 28.3% in all trials) (Table 2). GC for volume was generally higher than the GC basal area, again due to the additional variation caused by the inclusion of the height dataset in the calculation. The Nelson Berrymans trial was also the exception, where GC volume was slightly lower than the GC basal area values.

One or both *Trichoderma* treatments of PR6 and PR3a had significantly ($P<0.05$) reduced CV and GC statistics in three (Bay of Plenty/Waikato Kaingaroa 660/2, Northland Whatoro and Gisborne Tauwhareparae) of the eight trials compared to the control (Table 2). In addition, the Gisborne Patunamu trial had CVs for basal area and volume that were significantly lower in the PR3a treatment. Tree variability, when statistics were meaned over all trials, was significantly ($P<0.05$) lower in both *Trichoderm*a treatments by 10.3 to 13.9% (CV) and 9.2 to 11.4% (GC) compared to the control (Table 2). Therefore, this management tool had a homogenizing effect on the size of the trees in the plot, with fewer trees being very small and more trees in the central size classes (for example, Whatoro trial data, Figure 1). There was also no significant ($P<0.05$) difference in CV or GC statistics between the two *Trichoderma* treatments (Table 2). Therefore, both mixtures are recommended for forest companies that aim to produce timber of similar size and/or want to reduce production or harvest costs. Production costs could be reduced by refinement of the number or type of thinning and pruning operations or the number of inventory plots to obtain a desired level of precision in growth traits measurements. Harvest may be more effective and efficient due to better definition of harvest dates, less waste of small-diameter stems, and increased yield of similar-sized stems. Forests operating on low or no management inputs would also benefit from *Trichoderma* inoculation by taking advantage of reduced stem variability at harvest.

Table 1: Effect of *Trichoderma* treatments on mean tree survival (%), height (m), trunk diameter (mm), basal area (m^2) and individual tree and plot volume (m^3) in eight plantation trials approximately four years after establishment.

Region and Site	Treatment	Survival (%) [a]	Height (m)	Trunk diameter (mm) [b]	Basal Area (m^2) [c]	Tree Volume (m^3) [d]	Plot Tree Volume (m^3) [e]
Bay of Plenty / Waikato xPKANG 209/4	PR6	98.8 a	3.95 a	62.5 a	0.00324 a	0.00853 a	0.211 a
	PR3a	96.8 a	3.72 b	58.9 b	0.00289 b	0.00750 b	0.182 b
	Control	97.2 a	3.62 b	57.3 b	0.00279 b	0.00725 b	0.176 b
	LSD (5%)	**2.4**	**0.15**	**3.1**	**0.000301**	**0.00081**	**0.0188**
Bay of Plenty / Waikato xPKANG 660/2	PR6	98.4 a	3.87 a	58.1 a	0.00278 a	0.00723 a	0.177 a
	PR3a	97.2 a	3.82 a	58.4 a	0.00281 a	0.00732 a	0.178 a
	Control	98.0 a	3.59 b	53.5 b	0.00241 b	0.00624 b	0.152 b
	LSD (5%)	**2.3**	**0.14**	**3.4**	**0.000294**	**.00079**	**0.020**
Northland Topuni	PR6	96.1 a	4.74 a	69.5 a	0.00415 a	0.01167 a	0.280 a
	PR3a	99.5 a	4.73 a	68.8 ab	0.00403 ab	0.01170 a	0.291 a
	Control	91.5 b	4.09 b	60.6 b	0.00331 b	0.00907 b	0.208 b
	LSD (5%)	**4.2**	**0.3**	**8.7**	**0.00081**	**0.00235**	**0.067**
Northland Whatoro	PR6	95.2 a	4.91 a	98.9 a	0.00855 a	0.02441 a	0.562 a
	PR3a	94.4 a	5.01 a	98.5 a	0.00828 a	0.02604 a	0.528 a
	Control	93.6 a	4.50 b	83.8 b	0.00646 b	0.01830 b	0.422 b
	LSD (5%)	**4.7**	**0.31**	**8.9**	**0.00125**	**0.0054**	0.090
Gisborne Patunamu	PR6	92.3 a	6.85 a	109.4 a	0.00967 a	0.03173 a	0.690 a
	PR3a	94.2 a	6.74 ab	110.4 a	0.00981 a	0.03180 a	0.728 a
	Control	95.6 a	6.53 b	105.5 b	0.00904 b	0.02879 b	0.684 a
	LSD (5%)	**6.5**	**0.26**	**3.7**	**0.00062**	**0.0025**	**0.096**
Gisborne Tauwhareparae	PR6	91.5 a	6.10 ab	113.5 ab	0.0106 b	0.0329 b	0.739 b
	PR3a	90.7 a	6.29 a	118.1 a	0.0113 a	0.0356 a	0.760 a
	Control	86.4 a	5.71 b	108.9 b	0.0102 b	0.0318 b	0.663 b
	LSD (5%)	**11.7**	**0.41**	**8.1**	**0.00091**	**0.0036**	**0.097**
Nelson Sherry	PR6	92.0 a	4.48 a	68.5 a	0.00388 a	0.01055 a	0.232 a
	PR3a	94.8 a	4.51 a	69.7 a	0.00403 a	0.01101 a	0.256 a
	Control	91.4 a	4.39 a	68.8 a	0.00402 a	0.01099 a	0.244 a
	LSD (5%)	**6.6**	**0.37**	**6.8**	**0.00127**	**0.00218**	**0.063**
Nelson Berrymans	PR6	89.7 a	2.70 a	31.9 a	0.000895 a	0.00236 a	0.0516 a
	PR3a	92.0 a	2.73 a	33.4 a	0.001002 a	0.00263 a	0.0594 a
	Control	87.4 a	2.70 a	33.0 a	0.000954 a	0.00251 a	0.0538 a
	LSD (5%)	**9.3**	**0.19**	**4.9**	**0.000353**	**0.00063**	**0.0127**
Mean	PR6	94.3 ab	4.70 (7.1) a	76.5 (7.0) a	0.00547 (11.7) a	0.0162 (12.5) a	0.368 (13.0) a
	PR3a	95.0 a	4.69 (6.8) a	77.0 (7.7) a	0.00552 (12.7) a	0.0167 (16.1) a	0.373 (14.6) a
	Control	92.6 b	4.39 b	71.5 b	0.00490 b	0.0144 b	0.325 b
	LSD (5%)	**2.1**	**0.28**	**3.3**	**0.000431**	**0.00155**	**0.031**

[a] Letters were assigned according to a Fisher's 5% level unprotected LSD test. Two means with the same letter within each site and variable are not significantly (NS) different at $P<0.05$. The percentage increase in means for *Trichoderma* treatments compared to the untreated controls is in brackets.

[b] Trunk diameter (DBH) was measured at 1.4m above ground level.

[c] Basal area of an individual tree formula was $ba = 7.85\times10^{-5}\times DBH^2$.

[d] Under-bark stem volume of an individual tree (v) formula was v=h*ba*(B1*(h-1.4)**(-B2)+ B3), where h = height of an individual tree (m), ba = basal area of an individual tree (formula above) and f = individual-tree breast height volume form factors (derived from f = v/(ba×h; B1=0.86, B2=0.972 and B3=0.304) (Kimberley and Beets 2007).

[e] Plot volume was the sum of individual tree volumes in each plot.

Table 2: Effect of *Trichoderma* treatments on the CV (%) of tree height, diameter at breast height, basal area and under-bark stem volume and Gini Coefficient of basal area and under-bark stem volume in the 2018 trials approximately four years after planting.

Region and Site		CV (%) [a]				Gini Coefficient [b]	
	Treatment	**Height**	**DBH**	**Basal Area [b]**	**Volume [b]**	**Basal Area**	**Volume**
Bay of Plenty / Waikato xPKANG 209/4	PR6	17.4 a	23.9 a	45.6 a	47.1 a	24.4 a	25.6 a
	PR3a	16.7 a	24.2 a	47.6 a	48.6 a	25.5 a	26.4 a
	Control	17.7 a	27.8 a	52.8 a	53.8 a	27.4 a	28.2 a
	LSD (5%)	**2.8**	**4.3**	**8.0**	**8.4**	**4.0**	**4.1**
Bay of Plenty / Waikato xPKANG 660/2	PR6	14.8 b	21.2 b	40.8 b	42.7 b	22.0 b	22.8 b
	PR3a	15.3 ab	22.4 b	42.7 b	44.3 b	23.1 b	23.9 b
	Control	16.9 a	26.6 a	50.7 a	52.0 a	27.4 a	27.9 a
	LSD (5%)	**2.1**	**2.9**	**5.7**	**5.8**	**2.9**	**2.9**
Northland Topuni	PR6	20.3 a	28.5 a	51.9 a	56.4 a	28.4 a	30.5 a
	PR3a	22.7 a	32.1 a	60.0 a	66.5 a	31.7 a	34.6 a
	Control	22.8 a	35.7 a	64.8 a	69.1 a	34.3 a	36.3 a
	LSD (5%)	**4.5**	**8.7**	**14.8**	**14.3**	**6.7**	**6.4**
Northland Whatoro	PR6	21.1 b	31.3 b	51.4 b	55.2 ab	28.1 b	30.2 b
	PR3a	18.3 b	28.1 b	49.2 b	50.7 b	26.7 b	28.9 b
	Control	25.9 a	38.9 a	63.6 a	67.4 a	35.0 a	37.0 a
	LSD (5%)	**4.3**	**6.4**	**11.5**	**13.1**	**5.9**	**6.0**
Gisborne Patunamu	PR6	10.9 a	16.0 a	30.2 ab	35.0 ab	16.6 a	18.9 a
	PR3a	12.1 a	14.6 a	27.5 b	31.8 b	15.5 a	17.9 a
	Control	12.1 a	17.4 a	32.8 a	37.6 a	18.0 a	20.2 a
	LSD (5%)	**2.3**	**3.1**	**5.3**	**5.8**	**3.1**	**3.4**
Gisborne Tauwhareparae	PR6	15.7 b	19.1 b	35.7 ab	40.0 ab	19.0 ab	21.7 ab
	PR3a	14.4 b	17.4 b	31.8 b	36.3 b	17.1 b	19.5 b
	Control	23.0 a	26.0 a	43.4 a	49.1 a	23.7 a	26.0 a
	LSD (5%)	**5.9**	**6.6**	**9.6**	**9.2**	**4.3**	**4.5**
Nelson Sherry	PR6	16.3 a	21.4 a	40.8 a	44.2 a	21.9 a	23.6 a
	PR3a	15.0 a	19.5 a	37.4 a	40.6 a	20.1 a	21.7 a
	Control	17.5 a	22.7 a	42.0 a	44.1 a	22.7 a	23.8 a
	LSD (5%)	**4.6**	**5.3**	**10.1**	**9.5**	**5.0**	**4.6**
Nelson Berrymans	PR6	18.9 a	32.9 a	62.9 a	57.8 a	32.8 a	30.2 a
	PR3a	20.5 a	35.8 a	67.2 a	61.2 a	35.7 a	32.5 a
	Control	17.6 a	29.0 a	56.3 a	50.7 a	29.8 a	26.7 a
	LSD (5%)	**3.7**	**8.1**	**17.5**	**14.2**	**8.2**	**6.9**
Mean	PR6	16.9 (-11.8) b	24.3 (-13.3) b	44.9 (-11.6) b	47.3 (-10.7) b	24.2 (-11.4) b	25.4 (-10.0) b
	PR3a	16.9 (-12.0) b	24.3 (-13.9) b	45.4 (-10.6) b	47.5 (-10.3) b	24.4 (-10.5) b	25.7 (-9.2) b
	Control	19.2 a	28.0 a	50.8 a	53.0 a	27.3 a	28.3 a
	LSD (5%)	**2.2**	**3.0**	**4.7**	**5.1**	**2.5**	**2.5**

[a] Letters were assigned according to a Fisher's 5% level unprotected LSD test. Two means with the same letter within each site and variable are not significantly (NS) different at P<0.05. The percentage decrease in means for *Trichoderma* treatments compared to the untreated controls is in brackets.

[b] Formulae for basal area and under-bark stem volume of an individual tree are provided in Table 1.

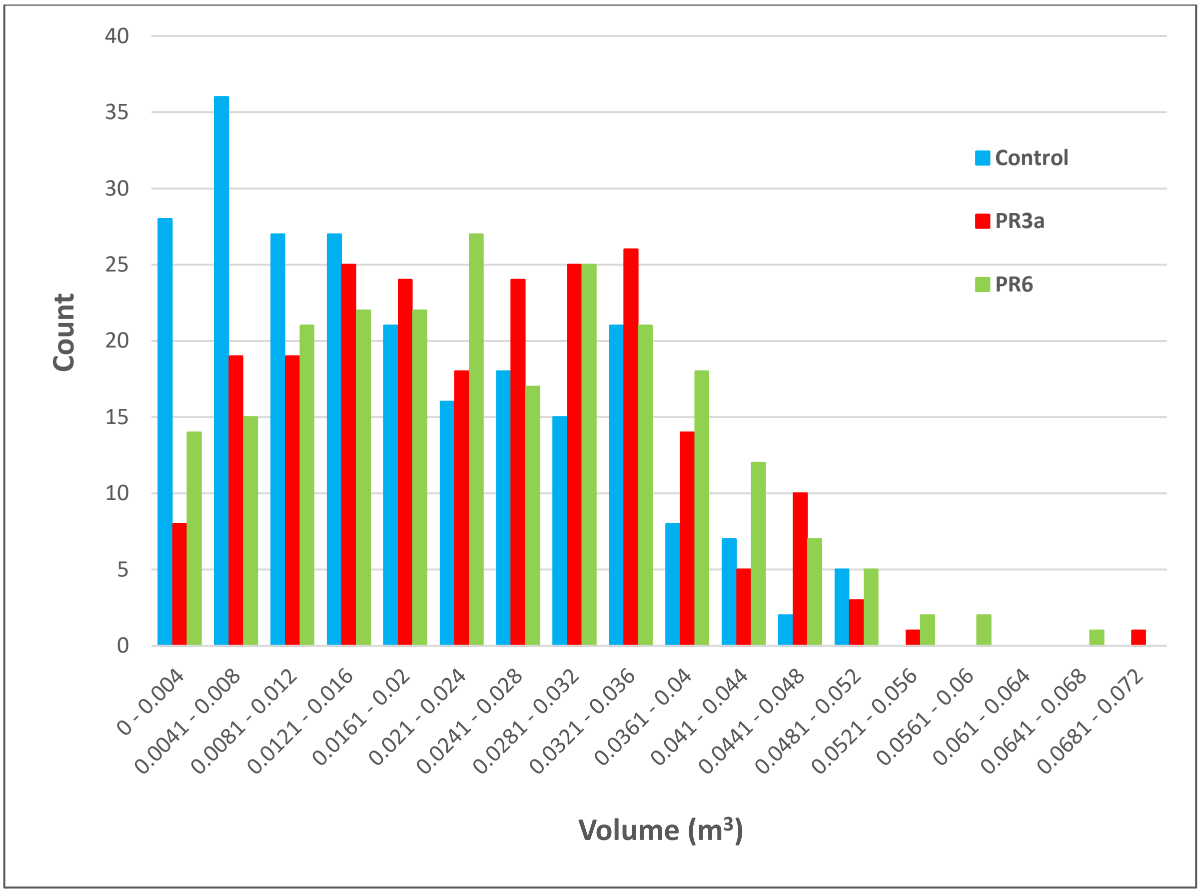

Figure 1: Frequency distribution of all individual tree volumes (m^3) in the control, PR3a and PR6 treatment plots in the Northland Whatoro trial four years after establishment.

The GC statistics found in these NZ plantations were similar to or less than those described in other studies of even-aged, single-species plantation forest stands. For example, Duduman (2011) observed GCs for tree basal areas in 18 Norway spruce, silver fir or beech forests of between 0.23 and 0.35. Similarly, Katholnig (2012) measured a mean GC for volume of 28.5 in 29 larch, oak and beech forests in Switzerland. The GC basal areas for the Gisborne Patunamu trial of 15.5, 16.6 and 18.0 were very low, indicating very little variability in the growing conditions for the development of each tree's trunk diameter. This trial was located on a warm site with a uniform orientated slope and relatively low altitude (200m asl) and weed pressure. In contrast, the Nelson Berrymans (26.7 to 35.7) and Northland's Whatoro (26.7 to 37.0) and Topuni (28.4 to 36.3) trials had approximately twice the GC statistics of those in the Patunamu trial. These trials had intense weed pressure with numerous weed species, variation in the slope orientation or location of plots and, in the case of Topuni, variable growing conditions within each plot due to the land-preparation method (herringbone ripping).

This study was undertaken in trees four years after establishment (but prior to canopy closure), when tree size uniformity is expected to be the highest during the life of the stand (Valbuena et al. 2016). At canopy closure, competition for light is generally considered the main competition process and can be characterized by strong asymmetry in stands, ie. larger trees monopolise light resources proportionally more than their size (Bourdier et al. 2016). The reduction in variability of height in the *Trichoderma* inoculated trees may lead to these trees reaching canopy closure in a more condensed timeframe, compared to untreated trees, resulting in less light competition, greater use efficiency and ultimately higher production (Stape et al. 2010). The trials should be monitored in the future to determine if the improvement in tree uniformity from the *Trichoderma* treatment is maintained at canopy closure and beyond.

The definition of the effect of *Trichoderma* on tree size variation was confounded by the presence of disease in some of the trials. Foliar disease, mainly *Dothistroma septosporum*, was measured at moderate levels (incidence of >93% and severity of 8 to 13%) in the Kaingaroa Forest 660/2 trial and at low levels in five other trials (incidence of 9 to 88% and severity of 1 to 7%). Disease may have contributed to tree size variation when present in the plots. For example, a significant (P<0.01) positive linear correlation between GC for plot tree volume and disease severity was found in the Kaingaroa Forest 660/2 trial (Figure 2). However, there was insufficient disease in the other trials to confirm this relationship.

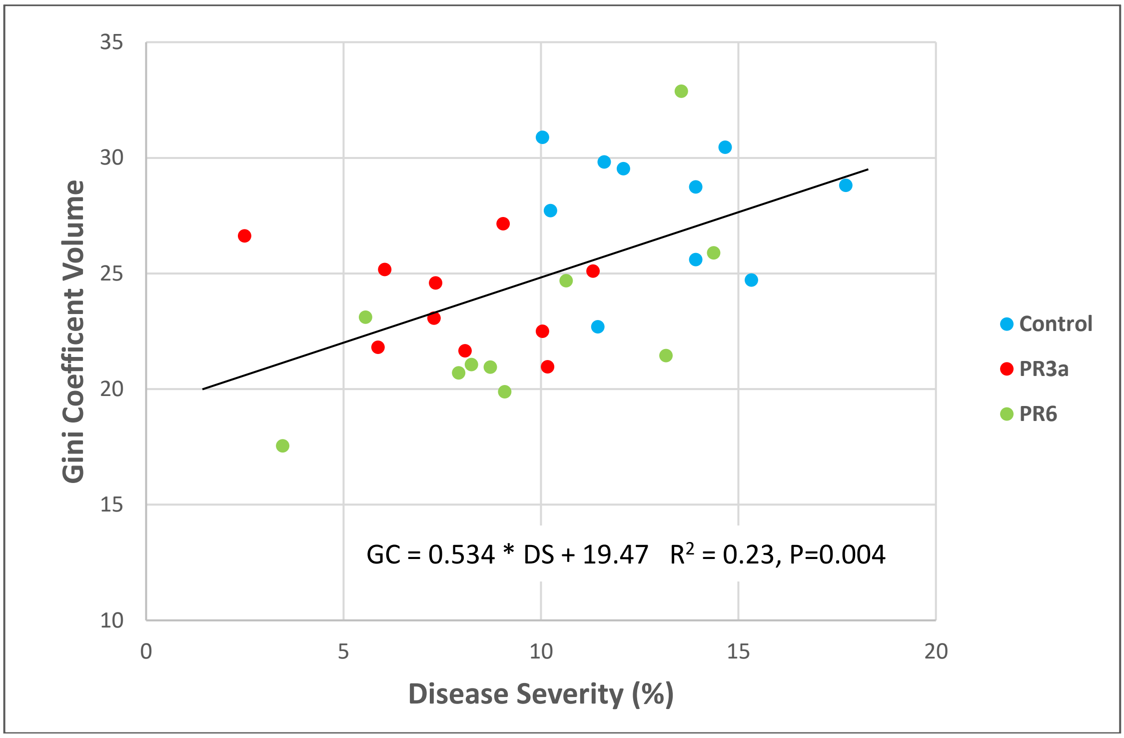

Figure 2: The relationship between Gini Coefficient (GC) for tree volume and *Dothistroma septosporum* disease severity (DS, %) in plots of the Kaingaroa Forest 660/2 trial on 17 August 2022.

Quantifying structure is of importance to forestry managers when the goal is to develop and manage a forest with low small-scale tree height and DBH variability. In this study, the CV and GC statistics had a strong positive linear correlation (P<0.001) for basal area (0.998) and volume (0.994) according to the Pearson correlation coefficient. Therefore, both CV and GC statistics provided a similar description of the effects of *Trichoderma* inoculation on plot tree size variation but differences in statistic derivation should be considered when interpreting the results. Both statistics were useful at providing an overview of plot tree size variability due to their simplistic and concise descriptions. The data required for both statistics, where an interaction between neighbouring trees has occurred, is often available using existing forest company resources (eg. from inventory plots that have a minimum of approximately 20 trees). In addition, no arbitrary classes for tree variables were required in both statistic types, increasing the accuracy of the results. The main advantage of the CV statistic was the ease of calculation in statistical programmes (often a standard procedure in statistical analysis). However, CV is obtained from the standard deviation, which calculates the dispersion of tree variables around their average, so describes a simplistic measure of variability. In comparison, GC is a more robust and efficient indicator of tree size variability due to its consideration of the differences among individual tree pairs.

GC has other advantages compared to CV, including being insensitive to datasets with small sample sizes, the presence of anomalously low or high values, or if the data are approaching a non-normal distribution (ie the presence of skewness or kurtosis). Overall, GC is recommended for the quantification of the effect of silviculture treatments (eg. nursery *Trichoderma* inputs) on tree size uniformity because it provides a robust, concise and efficient statistic that is directly related to size hierarchy and therefore a good indicator of asymmetric competition between trees. However, CV can be useful if a quick analysis is required.

This study gained information on stand uniformity based on datasets from eight plantation *Trichoderma* trials established in 2018 in the main forestry areas of the North Island and northern South Island (near Nelson). Additional trials in 2020 and 2021 have been established near Nelson and in Canterbury and Southern Otago (Whelan, 2021). Future studies of these trials would test the ability of *Trichoderma* inoculants to increase stand uniformity in forest areas with an extended range of environmental conditions. In addition, variability is likely to increase as the crop matures (Weiner and Thomas 1986) due to windthrow events, self-thinning or lower light availability after canopy closure, particularly if no silviculture thinning is undertaken. It would be valuable to determine if *Trichoderma* can continue to reduce variability compared to untreated trees as the crops approach harvest.

This study was reliant on ground-based data collected as part of research to determine if *Trichoderma* inoculants can promote tree growth and suppress foliar disease in plantation radiata pines. Although the data collected were very accurate, the process was time-consuming and labour-intensive. Airborne laser scanning (ALS) has been utilised to assess and monitor the structural complexity of pine forests on a large scale (Dash et al. 2016, Gavilán-Acuña et al. 2022). ALS technology, in combination with structural indices like GC, may provide cost-efficient opportunities for extensive monitoring of the impact of silvicultural practices like nursery *Trichoderma* tree inoculation on forest structure. This knowledge will become increasingly important for refining silviculture and harvest management practices as forestry development occurs in new areas due to Government policy (ie. One Billion Trees by 2028) and the impact of climate change extends the environmental boundary trees are grown in.

CONCLUSION

The GC, and to a lesser extent CV, were suitable summary statistics to describe the uniformity of growth traits in these trials. These indicators, in addition to mean tree size and density data, contributed to a better understanding of structural properties in plantation trees after being inoculated with *Trichoderma* in the nursery. GC and CV statistics identified that *Trichoderma* increased the uniformity of tree height, DBH, basal area and volume by 9.2 to 13.9% in the eight trials studied. The results of this study are relevant to foresters to aid in the optimisation of stand management practices at both a small (intensive) and large (extensive) scale to improve timber yield. The use of *Trichoderma* inoculants can be a practical and effective tool for reducing stand variability and allowing for better definition of thinning, pruning and harvest goals. Ultimately this leads to more sustainable and efficient use of forest resources.

Monitoring of these, and other *Trichoderma* trials recently established in environments with an extended range of growing conditions, would determine whether the uniformity effects of *Trichoderma* on stem size continue as the trees approach maturity.

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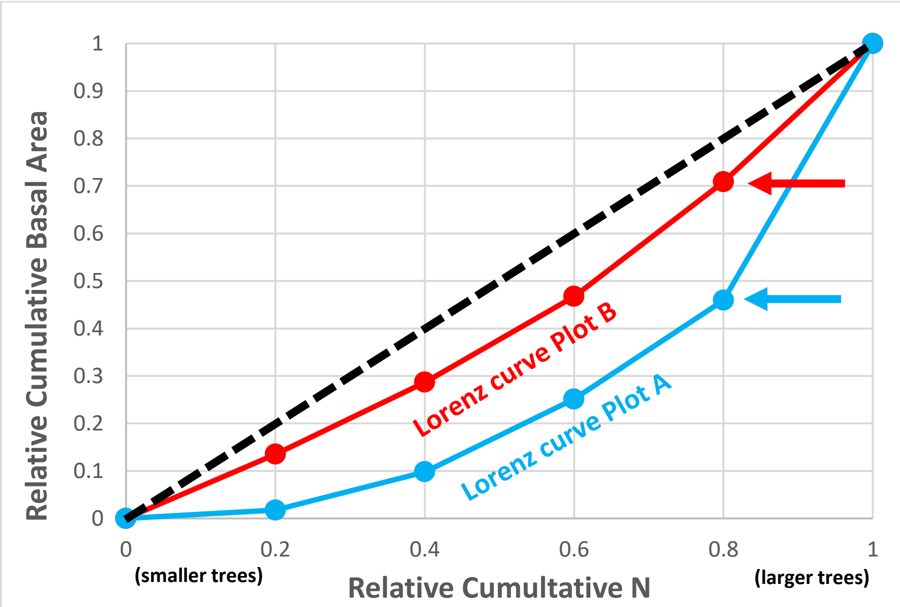
APPENDIX A:

An example of the calculation of the Gini coefficient for two plots with the same mean tree diameter at breast height (DBH) of 10.0cm but different levels of uniformity (Plot A has high, and Plot B has low uniformity of basal area respectively). The area under the Lorenz curve is calculated as the sum of trapezoids, each of which is calculated as $a_1 = (\Sigma ba_1 / BA + \Sigma ba_1\text{-}1 / BA) / 2 * (\Sigma n_1 / N – \Sigma n_1\text{-}1 / N)$. For example, the area for sample tree number 4 in Plot A is: $a_4 = (0.459 + 0.251) /2 * (0.8\text{-}0.6) = 0.0710$. The Gini coefficient for this plot (ie: the area under the Lorenz curve) is (0.5-0.265) / 0.5 = 0.47 or 47.0% and indicates a high uniformity of tree sizes in the plot.

Plot A with high uniformity of tree size:							
Sample Tree number	DBH (cm)	Σ n/N	Basal area (ba) (cm^2)	Σ ba	Σ ba/BA	Area under the Lorenz curve	Gini coefficient
1	5	0.2	8.552978775	8.552978775	0.017400058	0.001740006	
2	7.1	0.4	39.59188798	48.14486675	0.097945227	0.011534528	
3	10	0.6	75.4295759	123.5744427	0.251398076	0.03493433	
4	12.4	0.8	102.0702591	225.6447018	0.459048349	0.071044643	
5	15.5	1	265.9041776	491.5488794	1	0.145904835	
Σ			491.5488794			0.265158342	
mean	**10.0**						**0.47**
Plot B with low uniformity of tree size:							
1	7.8	0.2	54.10603378	54.10603378	0.134935558	0.013493556	
2	8.3	0.4	60.8211824	114.9272162	0.286618091	0.042155365	
3	9.9	0.6	72.3822336	187.3094498	0.46713284	0.075375093	
4	11.5	0.8	96.76882598	284.0782758	0.708465546	0.117559839	
5	12.5	1	116.8985639	400.9768397	1	0.170846555	
Σ			400.9768397			0.419430407	
mean	**10.0**						**0.16**



Lorenz curves for calculating Gini coefficients for Plots A and B where the relative cumulative basal area (Σ ba/BA) is plotted against relative cumulative N (Σ n/N). The blue arrow is the point for sample tree 4 in Plot A, where up to a DBH of 12.4 cm, 80% of the trees have a 45.9% share of the basal area of the stand. The red arrow is the point for sample tree 4 in Plot B, where up to a DBH of 11.5cm, 80% of the trees have a 70.8% share of the basal area of the stand. The dotted line represents the line of perfect equality, the area under the Lorenz curve for Plots A is 0.265 (GC = 0.47) and Plot B is 0.419 (GC = 16).