HARVEST TREATMENTS AND FERTILISER APPLICATION AFFECT TRANSPLANT STRESS INDEX OF *PINUS RADIATA*

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ABSTRACT

A simple method of assessing transplant stress was applied to data from three studies with bare-root *Pinus radiata* D. Don seedlings. A negative Transplant Stress Index (TSI) indicates seedlings have undergone transplant shock (the more negative the value, the greater the intensity of transplant stress). Negative TSI values occurred only during the first year after transplanting. Harvest treatments that included removing the forest litter affected TSI values on two sites. On one site, application of urea fertiliser increased the TSI. After the first year, TSI values were always positive. The TSI value appears to be a measure of seedling performance that is not directly related to either mean survival or mean initial height growth of the population. Stress Index can detect differences among treatments more quickly than comparisons of mortality.

Keywords: transplant shock; planting check; bare-root seedlings; establishment; site preparation; urea.

INTRODUCTION

Bare-root seedlings are lifted from nursery beds and stored in bags or boxes for a period of time before transplanting. After planting in the field, the seedlings often undergo what is called transplanting stress (Sands 1984). Transplanting stress is an ephemeral event and it might take only 5 months for *Pinus radiata* seedlings to recover (Sands 1981). However, in some situations conifer growth might be affected for more than a year (Mullin 1963). In theory, the length and intensity of transplanting shock will depend on the environment, the condition of the planting stock, and the care taken during planting. However, until recently there has not been a simple way to estimate either the length or intensity of transplanting shock.

When periodic measurements are recorded for a population of seedlings, a Transplant Stress Index (TSI) can be calculated (South & Zwolinski 1997). A negative TSI value indicates that transplant stress has occurred. The intensity of the transplant stress is determined by the value (more negative = more stress). A basic assumption behind the TSI theory is that negative values do not occur for non-transplanted seedlings. Therefore, the length of transplant stress can be estimated by determining how many months or years it takes before the TSI value becomes positive. However, to obtain an exact length of transplant stress requires data from non-transplanted trees (of the same genotype) under similar environmental conditions.

The TSI value can only be determined for a population of seedlings (it cannot be determined for an individual seedling). TSI values can differ even when growth, dieback, and mortality are the same among seedling populations.

Researchers who are only interested in evaluating the effects of certain treatments on survival or growth need not analyse TSI values. This is because TSI is different from survival and height growth and it is often not correlated with either. TSI is a new measure of the performance of seedlings. Although it has been used to compare stock-types in the United States (South *et al.* in press) and the United Kingdom (Jinks & Kerr 1999), to date TSI has rarely been applied in New Zealand. Therefore, three data sets with *P. radiata* were used to test four hypotheses: (1) for *P. radiata*, negative TSI values occur only during the year after transplanting (TSI_1); (2) removal of organic matter during harvesting does not affect TSI_1; (3) the application of urea does not affect TSI_1; and (4) blocks within a site do not affect TSI_1.

SITES AND METHODS

Transplant Stress Index

TSI is defined as the slope of the linear relationship between shoot height at the beginning of the growth period and height increment. The procedure requires repeated measures of heights of individuals at various times. Yearly measurements are the most common but monthly measurements can also be used. To lessen the impact of individual values, it is recommended that TSI values not be calculated for populations of less than 100 individuals. The TSI value for the first year after planting was obtained from the equation:

$$h_1 - h_0 = X_1 + TSI_1(h_0),$$

where h_0 = initial height at time of planting
h_1 = tree height at Year 1 (typically measured in mid-winter)
h_2 = tree height at Year 2 (typically measured in mid-winter)
h_3 = tree height at Year 3 (typically measured in mid-winter)
TSI_1 = Transplant Stress Index for Year 1
X_1 = the y-axis intercept for Year 1

Likewise, the TSI value for the second year was calculated using the equation: $h_2 - h_1 = X_2 + TSI_2(h_1)$. The third year TSI was determined from: $h_3 - h_2 = X_3 + TSI_3(h_2)$.

If conditions of the site and seedlings just before and after planting are favourable, initial TSI values might be positive (e.g., 0.4). However, when *P. radiata* seedlings undergo stress after planting, then the TSI_1 value might be negative. TSI_1 values as low as –0.6 have occurred for *P. radiata* (Euan Mason, University of Canterbury, pers. comm.). The lowest TSI_1 value reported so far has been –0.7 for *Picea sitchensis* (Bongard) Carrière in Scotland (South & Zwolinski 1997).

Woodhill Trial

This study was located in the Woodhill Forest, a 9000-ha plantation of *P. radiata* established on sand dunes along the west coast of the North Island north of Auckland. The area has a mild, maritime climate (Table 1). Bare-root seedlings (1+0) were hand-planted in July 1986 at a 2 × 2-m spacing and their height was measured in August. At this time, seedling heights ranged from 9 to 38 cm (mean 21 cm). Subsequent height measurements were taken on an annual basis in mid-winter. The factorial study was arranged as a randomised complete block design (3 blocks; 4 site treatments; 2 split-plot fertiliser treatments). The study contained 2400 seedlings but only 815 seedlings were measured during the first year. The three "core" site treatments were:

(1) whole-tree harvest, with forest litter removed;

(2) whole-tree harvest; and

(3) stem-only harvest plus a single layer of harvest slash. At this site, a fourth treatment was included which involved a stem-only harvest plus a double layer of harvest slash.

Forest litter was removed only from Treatment #1 and organic matter remaining after harvest was related to treatment (#1 = least, #2 = more than #1, #3 = more than #2, and #4 = most). Urea was applied to half the subplots at 3-month intervals at a rate of 50 kg N/ha per application (200 kg N/ha·yr from September 1986 till August 1991). Details of the harvest and fertiliser treatments have been given by Smith, Dyck, Beets, Hodgkiss, & Lowe (1994) and Smith, Lowe,Beets, & Dyck (1994). Weed competition was virtually eliminated manually and with herbicides throughout the trial (details have been presented by Dyck *et al.* 1991).

TABLE 1–Soils, location, and climate for the three sites (Anon. 1983; Hewitt 1992).

	Woodhill	Kinleith	Golden Downs
Soil type	Pinaki sand	Taupo sandy loam	Spooner Hill Soil
Latitude (S)	36°43′	38°14′	41°36′
Longitude (E)	174°24′	175°58′	172°53′
Distance from coast (km)	2	60	40
Elevation (m)	30	490	450
Mean February temp (°C)	18.9	18.4	15.5
Mean July temp (°C)	10.3	7.4	4.6
Mean annual temp (°C)	14.3	13.2	10.4
Annual precipitation (mm)	1330	1420	1340

Kinleith Trial

A companion study was installed on a cut-over site at the Kinleith Forest in the central North Island (Table 1). In addition to the three "core" harvest treatments (described above), two other treatments were included. The fourth treatment involved a stem-only harvest with a V-blade treatment (to facilitate hand planting). Weed competition in these four treatments was virtually eliminated manually and with herbicides throughout the trial. The fifth treatment involved a stem-only harvest with no weed control at time of establishment. Bare-root seedlings (1+0) were hand-planted in August 1992 at 2 × 2-m spacing. At the initial measurement in November, seedling heights ranged from 4 to 52 cm (mean 27 cm). The factorial study was established as a randomised complete block design (4 blocks; 5 site treatments; 2 split-plot fertiliser treatments). Each square plot contained 100 measurement trees. The entire study contained 4000 seedlings. Seedling heights were measured on an annual basis in mid-winter. One year after planting, urea was applied to half of the subplots. At 3-month intervals, urea was applied at a rate of 50 kg N/ha·application (200 kg N/ha·yr from August 1993 till July 1998).

Golden Downs Trial

A third study was installed on a cut-over site at the Golden Downs Forest at the northern part of the South Island (Table 1). The treatments were: (1) whole-tree harvest with forest litter removed, (2) whole-tree harvest, and (3) stem-only harvest plus a single layer of harvest slash. Bare-root seedlings (1+0) were hand-planted in July 1994 at a 2 × 2-m spacing. At the initial measurement, seedling heights ranged from 9 to 52 cm (mean 29 cm). Subsequent measurements were taken on an annual basis in mid-winter. The factorial study was arranged as a randomised complete block design (4 blocks; 3 site treatments; 2 split-plot fertiliser treatments). The study contained 2400 seedlings. Seedling heights were measured on an annual basis in mid-winter. Urea was applied to half the subplots at 3-month intervals at a rate of 50 kg N/ha·application (200 kg N/ha·yr from October 1994 till September 1999). Weed competition was virtually eliminated manually and with herbicides throughout the trial.

Data Analysis

Split-plot analyses of variance of TSI were conducting using a General Linear Model procedure in a SAS-PC program (SAS 1988). Block and treatment factors were tested for significance using "Error A" (Block × Treatment) while the fertiliser and interaction factors were tested using "Error B" (Block × Treatment × Fertiliser). When overall treatment effects were significant at $\alpha \leq 0.05$, means were compared using Duncan's multiple-range test. Data on seedling dieback (where $h_0 > h_1$) were not analysed because few trees exhibited dieback. Relationships between TSI_1 and survival or first-year growth were examined using PROC CORR (SAS 1988).

RESULTS AND DISCUSSION

Negative TSI values were observed during the first year after transplanting but only positive values occurred for the second year (Table 2). Therefore, hypothesis #1 was not rejected. This suggests that severe transplanting stress for *P. radiata* in New Zealand does not last more than 1 year after transplanting. In contrast, trials with other bare-root species in different environments produced negative TSI values for 2 years after planting (South & Zwolinski 1997; Jinks & Kerr 1999).

Hypothesis #2 was rejected since harvest treatments affected TSI_1 at Kinleith and Golden Downs (Table 3). At both sites, removing the whole tree and the forest litter lowered the TSI_1 value (in comparison to the stem-only treatment). At Kinleith, stress was increased due to removal of the forest litter. Litter removal also lowered soil nitrogen reserves (Smith, Dyck, Beets, Hodgkiss, & Lowe 1994). The lack of significant treatment effects at Woodhill for TSI_1 might be related to fewer blocks and fewer trees measured per plot. Only 34 trees were

TABLE 2–First-year survival and first-, second-, and third-year transplant stress index (TSI) values for various harvest and fertiliser treatments at Woodhill, Kinleith, and Golden Downs. Values in the same column within a site followed by the same letter are not significantly different (p = 0.05).

Site	Treatment	Survival	TSI		
		(%)	Year 1	Year 2	Year 3
Woodhill	Whole tree with no litter	97	–0.1	0.6	0.7
	Whole tree	97	–0.1	0.5	0.4
	Stem only	98	0.0	0.4	0.5
	Stem only with double slash	89	0.3	0.3	0.6
	No fertiliser	97	0.2	0.4	0.5
	Fertiliser	93	–0.2	0.4	0.6
Kinleith	Whole tree with no litter	99	–0.1b	0.7	0.4
	Whole tree	96	0.1a	0.7	0.4
	Stem only	86	0.1a	0.8	0.4
	Stem only V-blade	98	0.0a	0.6	0.2
	Stem only no herbicide	90	0.1a	0.6	0.4
	No fertiliser	93	—	0.6	0.4
	Fertiliser	94	—	0.7	0.4
Golden Downs	Whole tree with no litter	99	0.0b	0.2	0.4
	Whole tree	99	–0.1b	0.1	0.4
	Stem only	96	0.3a	0.2	0.4
	No fertiliser	99	–0.1b	0.1	0.5a
	Fertiliser	98	0.2a	0.2	0.3b

TABLE 3–Probability values by location, source, and year for the TSI variable.

Location	Source	d.f.	Probability of a greater F-value		
			Year 1	Year 2	Year 3
Woodhill	Block	2	0.35	0.78	0.48
	Treatment	3	0.46	0.59	0.59
	Error A	6			
	Fertiliser	1	0.24	0.99	0.59
	Treatment × fertiliser	3	0.55	0.78	0.14
	Error B	8			
Kinleith	Block	3	0.51	0.42	0.14
	Treatment	4	0.01	0.23	0.20
	Error A	11			
	Fertiliser	1	—	0.39	0.74
	Treatment × fertiliser	4	—	0.54	0.29
	Error B	16			
Golden Downs	Block	3	0.80	0.21	0.61
	Treatment	2	0.02	0.70	0.98
	Error A	6			
	Fertiliser	1	0.01	0.11	0.02
	Treatment × fertiliser	2	0.75	0.55	0.73
	Error B	9			

initially measured per plot at Woodhill but 100 trees were measured per plot at the other two sites. Variation among the slope estimates will decrease with an increasing sample size. South & Zwolinski (1997) recommended that 100 or more trees be used to determine TSI values. This limitation should be kept in mind when designing and measuring future TSI studies.

In this study, initial survival was not positively related to TSI_1 (Table 4). At Woodhill, the treatment with the lowest survival had the highest TSI_1 value. At Kinleith, the opposite was observed (Table 2). This suggests that survival is not a good predictor of TSI_1. Therefore, TSI_1 is a more sensitive method of detecting transplanting stress than analysing survival.

TABLE 4—Pearson correlation coefficients (r) between first-year TSI and first-year survival and height growth. Values in parentheses are probabilities of a greater absolute value of r.

Location	N	Correlation coefficient	
		Survival	Height growth
Kinleith	10	–0.21 (0.55)	–0.31 (0.37)
Golden Downs	6	–0.43 (0.39)	0.01 (0.98)
Woodhill	8	–0.06 (0.88)	–0.37 (0.37)

At Golden Downs, urea applications increased the TSI_1 value (from –0.1 to +0.2). This finding rejects the hypothesis that fertiliser application does not affect TSI_1. At this site, treated seedlings grew 50 cm and untreated seedlings grew 44 cm (p=0.02).

Hypothesis #4 was not rejected since block did not affect TSI at any site. This may have occurred due to site homogeneity. In theory, when site conditions vary significantly, TSI_1 will be more negative on the more stressful sites.

Seedling dieback during the first year was less than 1% (Golden Downs = two seedlings; Kinleith = 38 seedlings; Woodhill = two seedlings). First-year height growth was lowest at the Kinleith site (Golden Downs = 47 cm; Kinleith = 23 cm; Woodhill = 46 cm). However, there appeared to be no correlation between initial growth and TSI_1 (Table 4). This supports the view that TSI_1 is a measure of seedling performance that is somewhat independent of initial height growth.

TSI_2 was positive for all second year means. Neither harvest treatment nor fertiliser application affected TSI_2. TSI_2 values were higher at the Kinleith site than at the Golden Downs site, even though height growth during the second year was about the same (Golden Downs = 75 cm; Kinleith = 77 cm; Woodhill = 46 cm).

TSI_3 values were positive for the third year and were affected only by fertiliser application at one site. The reason why treated trees at Golden Downs had lower TSI_3 values is not know but it might be due to a reduction in the allocation of carbohydrates to fine roots (Beets & Whitehead 1996). TSI_3 values were generally higher at Woodhill than at Golden Downs, even though average height growth was greater at Golden Downs (Golden Downs = 144 cm; Kinleith = 115 cm; Woodhill = 85 cm). After the third year, TSI values at the Woodhill site declined as stand height increased (TSI_4 = 0.3; TSI_5 = 0.1). This decline in TSI over time was not due to an increase in transplant stress but was due to a combination of increasing variation as well as a natural pattern of height growth as a function of tree size.

CONCLUSIONS

Since negative TSI values were not observed for the second year, it appears that severe transplant stress of *P. radiata* in New Zealand does not last for more than 1 year. On some sites, the method of site preparation can affect the TSI values. Removing the forest litter and whole tree during harvest can increase seedling stress (as indicated by TSI).

When attempting to define the length or intensity of transplanting stress, TSI has more utility than simply measuring growth, dieback, or mortality. This is because seedling stress can occur even when there is good growth, no dieback, and no mortality. Although it does not provide information about the underlying cause of stress, it does provide researchers with an objective index that is relatively easy to calculate.

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