INTERPINE

Forestry Innovation

Analysis and Interpretation of the 2010 FCM Dataset

Task 1.

Prepared for **New Zealand Forest Owners Association**

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1 EXECUTIVE SUMMARY

In 2010 Interpine Forestry Limited measured forest condition indicators in 190 plots across New Zealand on behalf of the New Zealand Forest Owners Association. The aim of the measurement is to provide a national survey which can detect changes in the condition of the national radiata estate in New Zealand. In accordance with procedures in other parts of the world crown condition as assessed through transparency and defoliation is used as the primary indicator for tree health and vigour. This document provides a presentation and interpretation of the data collected in 2010. Specific reference is given to identifying geographical patterns, rather than temporal patterns in the data, as no time series data is available yet. A methodology for correcting for the effect of changing age structure in the national estate is described and a correlation analysis trend analysis is undertaken to look for explanatory patterns in the condition dataset based on independently acquired spatially specific data.

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3 INTRODUCTION

3.1 A NEW ZEALAND WIDE FOREST CONDITION MONITORING SYSTEM

Over the past one hundred years New Zealand has established a significant exotic forest estate with *Pinus radiata D.Don* (Radiata pine) the primary plantation species. New Zealand's forests form an important basis for economic activity, provide significant recreational, conservation and cultural values, and make an important contribution to climate change mitigation. During winter 2010 Interpine Forestry Limited (Interpine) were contracted by the New Zealand Forest Owner's Association (NZFOA) to design and implement a forest condition monitoring (FCM) programme for New Zealand. The objective of the FCM programme is to detect temporal changes in forest condition through repeated measurements of tree and crown condition indicators over several years. This document represents an analysis and interpretation of the results gathered during the first year's measurement period with reference to independent datasets where appropriate.

3.2 THE 2010 FCM DATA SET

The FCM measurement programme was carried out between 5th May and the 30th of August 2010 and was carried out on all sites measured as part of the Ministry for the Environment's (MfE) carbon measurement survey. In total 4139 radiata pine trees were available for assessmebt of forest condition indicators across 190 plots established on a grid network with a randomly located start point. Two plots were abandoned because of physical barriers to plot establishment and no trees were assessed for forest condition indicators in these plots. A total of ten data collection staff were used during the measurement phase and generally a minimum of two crews were operating in different parts of New Zealand at any one time.

Forest condition was assessed as per the procedures set out in the New Zealand FCM manual[1]. The indicators used to provide a measure of forest condition are presented in Table 1. Summary statistics and information for each indicator can be reviewed in previous work[2] while the remainder of this document is concerned with the interpretation and analysis of the results of the defoliation and transparency indicators.

[1] Forest Condition Monitoring (FCM) of Pinus radiata in New Zealand. Field Data Collection Procedures. Prepared by Interpine Forestry Limited on behalf of NZFOA.
[2] Forest Condition Monitoring (FCM) Programme. 2010 Report Prepared by Interpine Forestry Limited on behalf of the NZFOA.

Table 1. The crown condition indicators used in the 2010 forest condition monitoring programme

Indicator	Scale				
Description	***0***	***1***	***2***	***3***	***4***
Entire Crown Transparency The amount of skylight visible through the live, normally foliated portion of the tree crown.	0 – 100% transparency classes (5% classes)				
Top 50% Crown Transparency The amount of skylight visible through the live, normally foliated portion of the top half of the crown.	0 – 100% transparency classes (5% classes)				
Crown Defoliation The amount of needle loss in the assessable crown as compared to a reference tree.	0 – 100% defoliations classes (5% classes)				
Stem Visibility The amount of stem visible through the foliage and branching.		Less than 25% of stem visible	25 – 50% of stem visible	50 – 75% of stem visible	More than 75% of stem visible
Needle Retention The number of needle age classes (to nearest year) present in the lower third of the unsuppressed green crown.	1 yr old needles absent	1 yr old needles present	2 yr old needles present	3 yr old needles present	4 yr old needles present
Crow Dieback The recent dieback of branches with fine twigs in the upper and outer portions of the tree.	0 – 100% crown dieback (in 5% classes)				
Crown Depth The depth of green foliage present in the crown.		Green foliage in lower quarter of crown	Green foliage in lower-mid quarter of crown	Green foliage in upper-mid quarter of crown	Green foliage in upper quarter of crown
Dothistroma Presence of *Dothistroma septosporum* which causes needles to turn brown with red bands.	0 – 100% of total crown foliage with infection (5% classes)				
Resin Bleeding Resin evident on the outside of the tree	Not assessed	Nil or light resin bleeding	Moderate resin bleeding	Severe resin bleeding	

3.3 Crown Condition

The visual assessment of crown condition is a widely used and scientifically valid indicator of tree health and is the basic indicator used in surveys of forest condition throughout Europe and North America. Crown condition is influenced by a number of biotic and abiotic stressors of which tree health is only one and it is important to identify and characterise sources of variation to improve our understanding. Other factors which may influence crown condition include climate, soil condition and tree age and it is important that the effects of these factors on crown condition can be understood and where possible distinguished from changes in tree health during analysis.

3.4 Analytical Objectives

Successful analysis depends on the proper specification of the analytical objectives. Analyses of crown condition are often based along four major themes; description, detection, evaluation and intensive site monitoring (Shomaker et al 2007) and it is advised that once a significant time series data set is accumulated over several years this approach can be followed in its entirety. At the current time the authors of this report aim to follow a descriptive approach which may lead towards the early stages of a detection analysis which will serve as a starting point and guide further work in this field in New Zealand. The descriptive approach employed involves the presentation and discussion of tabular and graphic summaries of population statistics, while useful for establishing a base line and for identifying gross differences among observation sets this type of trend analysis cannot identify forest condition change issues. To form a baseline for forest condition change detection an auxiliary statistical analysis will also be undertaken.

The NZFOA have also indicated a desire for a geographical comparison of the FCM plots and so a significant geographical information system (GIS) analysis component has also been undertaken as part of this project.

4 Analysis, Presentation and Interpretation of the Survey Results

4.1 Scientific Rationale

A tree's vigour is the product of the interaction of numerous biotic and abiotic factors including both physiological and external factors. These factors often manifest in the physical appearance of the tree's crown. When natural or anthropogenic stresses impact the health of a forest ecosystem the first signs of deterioration can generally be observed in the tree crowns. The crowns of forest trees form a fundamental component of the forest ecosystem and are the major determinant of net primary productivity; therefore the assessment of tree crown condition provides valuable insight into tree and forest health (Schomaker et al. 2007).

Crown condition is the primary indicator of tree condition used throughout Europe (Feretti 1996, Anon 2007) and North America (Smith and Conkling 2004). Examples of studies illustrating the link between crown condition are widespread and numerous throughout the world (See Schomaker et al. 2007 for a review). There can be no doubt that the long-term repeated monitoring of crown condition at a national or regional scale provides an insight into changes in tree and forest health. However, the factors affecting crown condition are numerous and the relationship between crown condition and tree vigour is complicated by forest dynamics and abiotic factors. To further the understanding of crown condition in radiata pine in New Zealand the analysis detailed in this document has several objectives:

- To summarise the forest condition data collected during the 2010 measurement period;
- To look for spatial patterns in the dataset (temporal changes cannot be assessed until further crown condition assessments are made);
- To use pre-existing independent datasets to derive explanatory variables for any patterns observed.

4.2 Classification of Defoliation Data

Defoliation is a crown condition indicator which is believed to be strongly correlated with tree vitality; trees that are fully foliated are healthy. It is possible to assign indicator thresholds to forest condition variables which are correlated with tree health based on a biological basis. These allow the categorisation of the likely physiological effect of the defoliation variable the categorisation outlined in Table 1 is used by the European forest condition monitoring network. It should be noted that this is a practical convention, useful for comparison purposes, as the actual physiological effect of defoliation is unknown.

Table 2. Defoliation classes according to UNECE and EU classifications (Fischer et al. 2010)

Defoliation Class	% defoliation	Degree of defoliation
0	Up to 10%	None
1	>10 – 25%	Slight (warning stage)
2	>25 – 60%	Moderate
3	>60 - <100%	Severe
4	100%	Dead

According to the classifications in Table 1 trees with defoliation score of 10% or less are discounted and a defoliation class of 10 – 25% is considered a warning stage. A defoliation of greater than 25% is deemed to be the threshold for damage and trees in defoliation class 2, 3, or 4 can be thought of as damaged as they are considerably defoliated (Lorenz et al. 2010).

4.3 DEFOLIATION RESULTS

In the 2010 survey defoliation was assessed on 4043 live radiata pine trees. Of the trees assessed 4.3% were scored as damaged, i.e. had a defoliation score of more than 25%. The percentage of trees in each of the defoliation classifications set out Table 1 is displayed in Figure 1. The mean defoliation for all trees in the 2010 survey was 7.5% and the median was 5%. The vast majority of trees (75.88%) displayed no evidence of defoliation and a further 19.79% were assessed as having only slight defoliation.

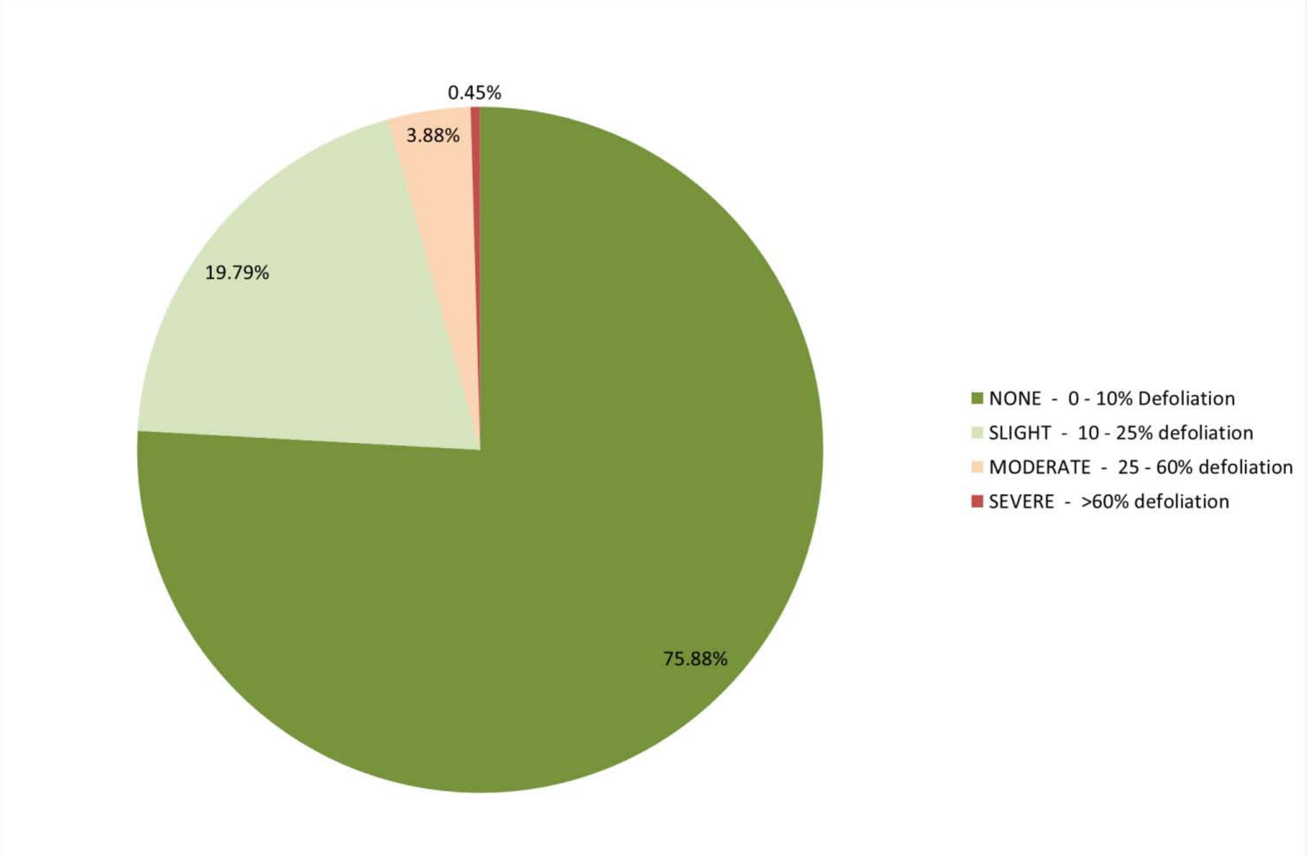


Figure 1. The percentage of trees in the four defoliation classes in the 2010 survey

Defoliation was plotted against tree age (Figure 2) and a linear regression was fitted to the data to describe the relationship. A weak correlation was found between defoliation percentage and age using a Pearson’s product-moment correlation test (0.443).

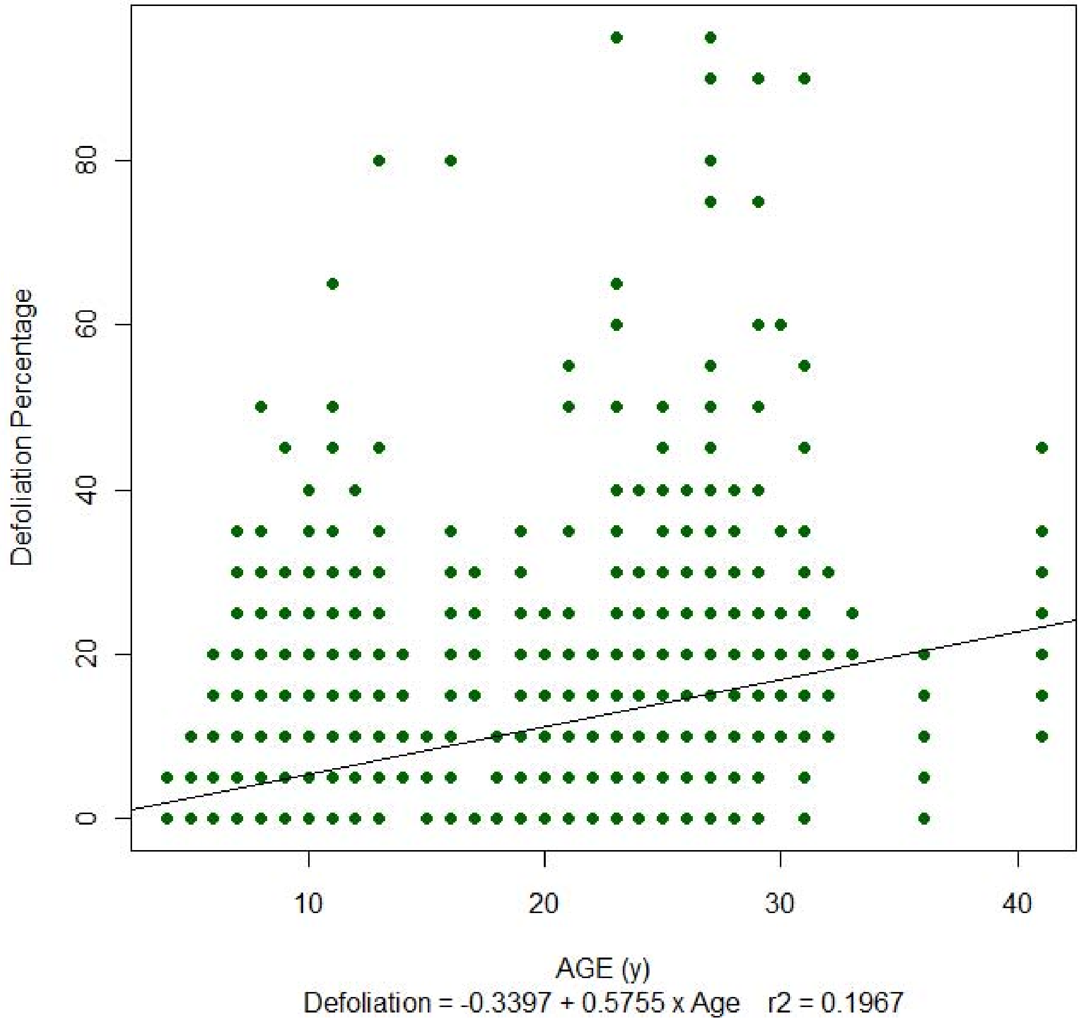


Figure 2. The relationship between defoliation percentage and age for trees in the 2010 survey

4.4 GEOGRAPHIC DISTRIBUTION OF DEFOLIATION RESULTS

Defoliation data was collected in plots throughout the country and so some inference into spatial trends in the data may be drawn. The defoliation data segregated by region is presented in this section but it must be noted that the sampling design for this survey was produced with the objective of providing summaries at the national level and so there may be insufficient plots to provide accurate summaries for specific regions. The number of trees assessed in each region and the regional mean and median defoliation scores are in Table 3 and the percentage of trees in the different defoliation classes is shown in Figure 3. There is considerable variation in the sample size for each region reported in Table 3, Canterbury in particular is under represented with only 20 trees but the Auckland and West Coast regions also have a small sample size. The Central North Island contains the largest proportion of New Zealand's radiata pine estate and this is well represented in the data set.

Table 3. Descriptive statistics for defoliation by region

	Sample Size	Mean	SD	Variance	Median
Auckland	99	0.51	1.81	3.31	0
Canterbury	20	15.75	6.57	45.46	15
Central North Island	1758	4.78	9.28	86.16	0
East Coast	375	3.84	6.98	48.85	0
Hawkes Bay	230	7.91	11.58	134.71	0
Nelson and Malborough	507	11.03	10.38	107.94	10
Northland	444	11.04	12.55	157.95	5
Otago and Southland	361	13.92	10.87	118.41	10
Southern North Island	156	6.31	9.63	93.26	0
West Coast	93	20.81	11.94	144.18	20

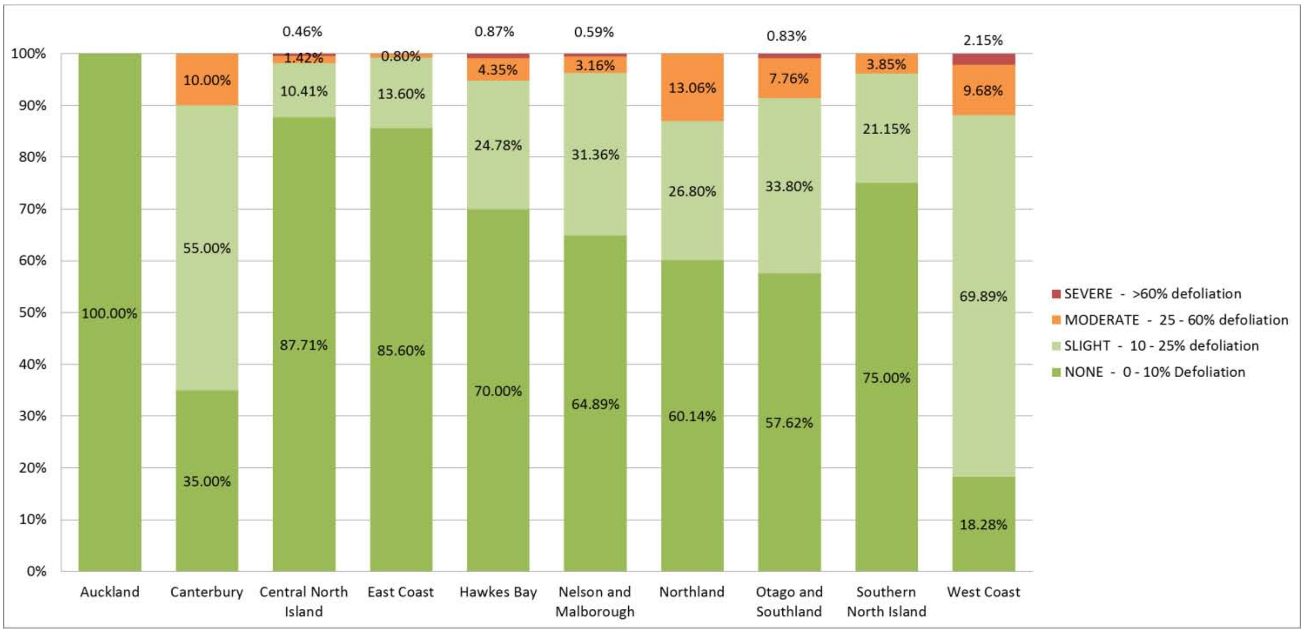


Figure 3. Percentage of trees in different defoliation classes by region.

Time series defoliation data for New Zealand is not yet available so the emphasis currently has to be placed on spatial trends. To determine the presence of any spatial trends maps have been prepared displaying the distribution of mean defoliation for the plots in the 2010 survey. The maps display the mean of crown condition indicator for each site and the each plot has been expanded to cover an 8km area for ease of visual reference. Figure 4 displays the mean defoliation score for plots in New Zealand.

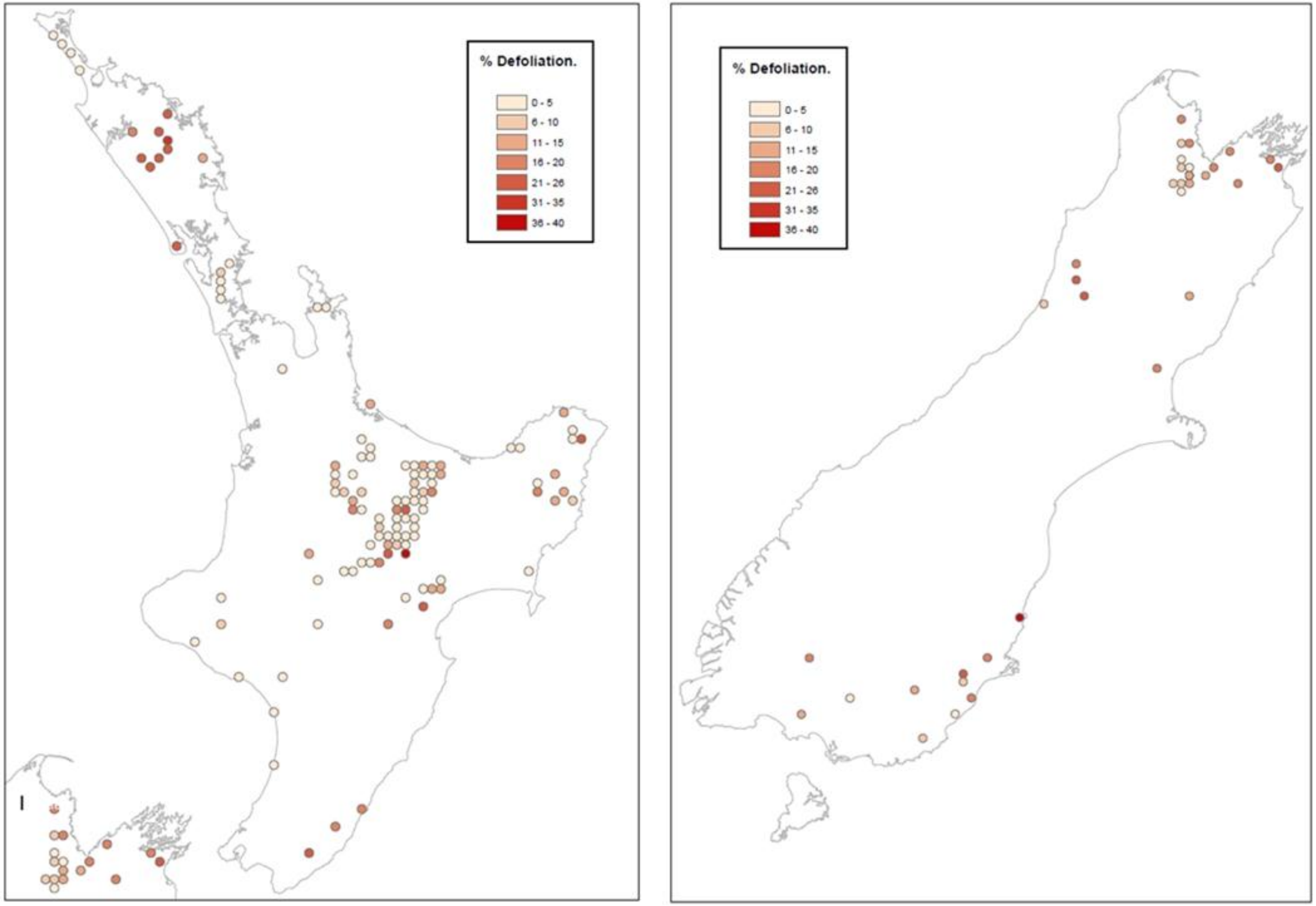
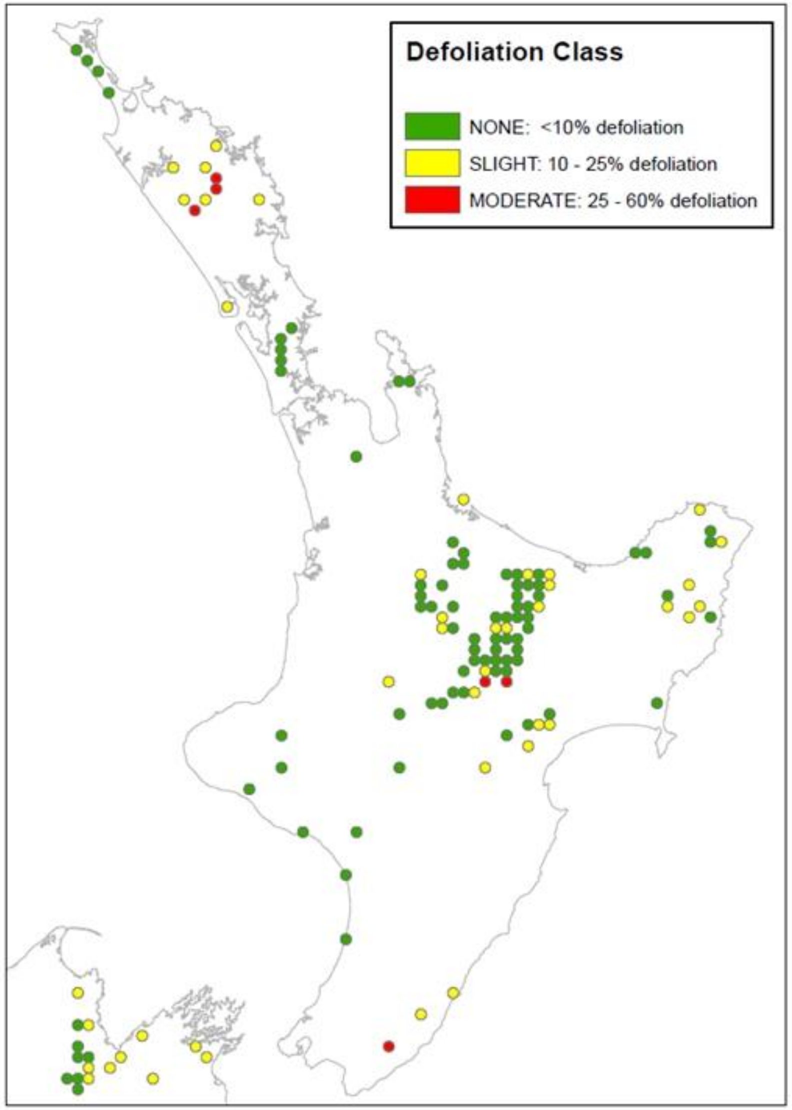


Figure 4. Patterns of mean defoliation in the 2010 measurement of the FCM plot network



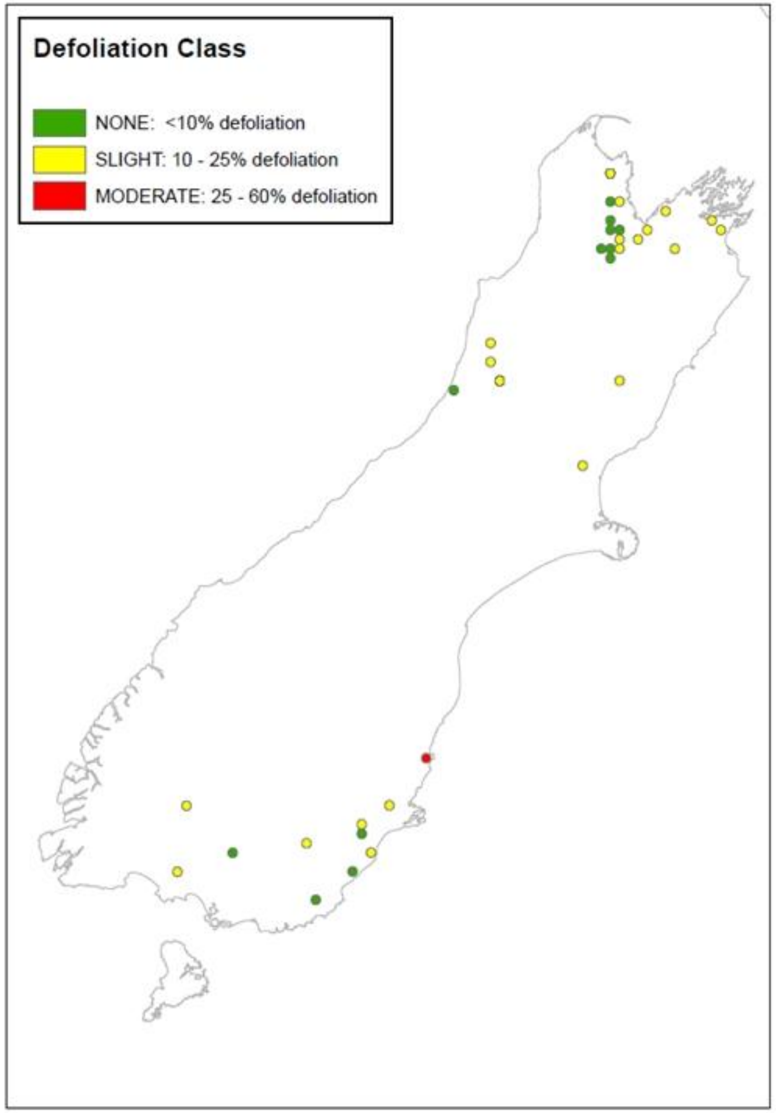


Figure 5. Patterns of defoliation class based on mean defoliation for the plots in the 2010 survey.

4.5 Crown Transparency Results

In the 2010 survey 4043 live radiata pine trees were assessed for crown transparency, both the transparency of the entire crown and the top 50% of the crown was assessed. Histograms of the crown transparency data measured are presented in Figures 6 and 7. The mean crown transparency for the entire crown was 45.88% and the median was 45%. The mean crown transparency for the top half of the crown was 33.5% and the median was 30%.

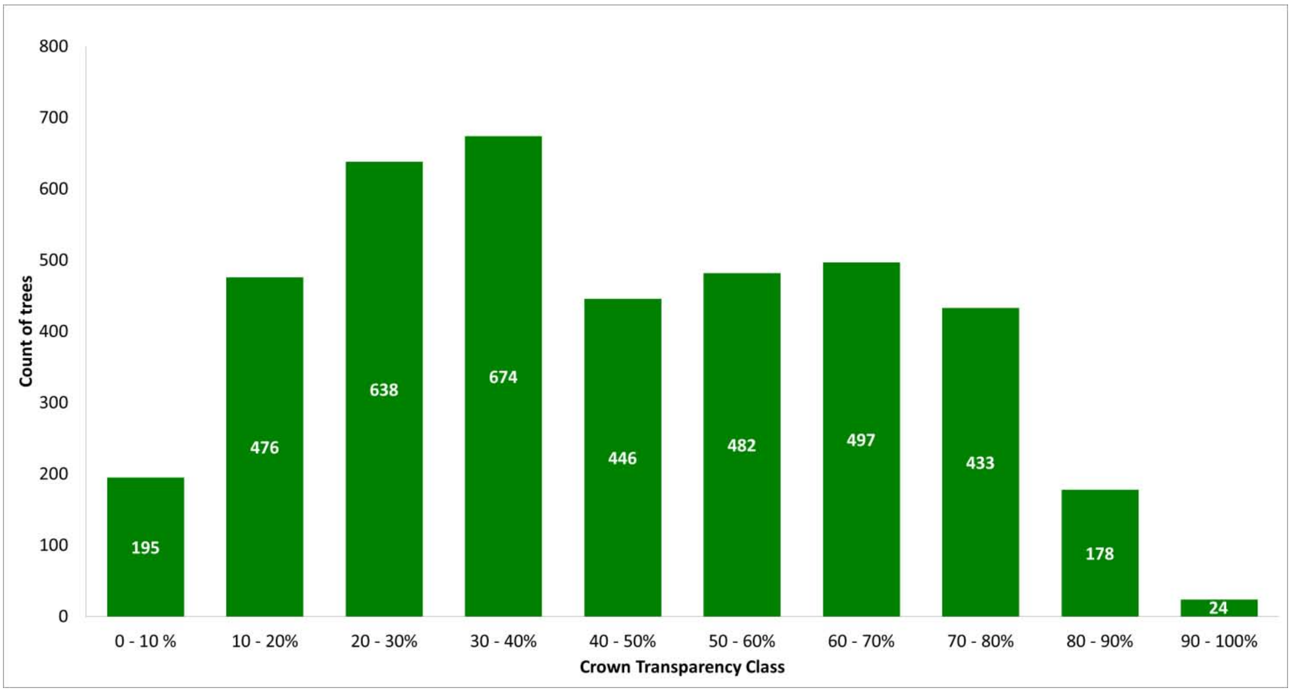


Figure 6. Histogram of crown transparency of entire crown for the trees in the 2010 survey

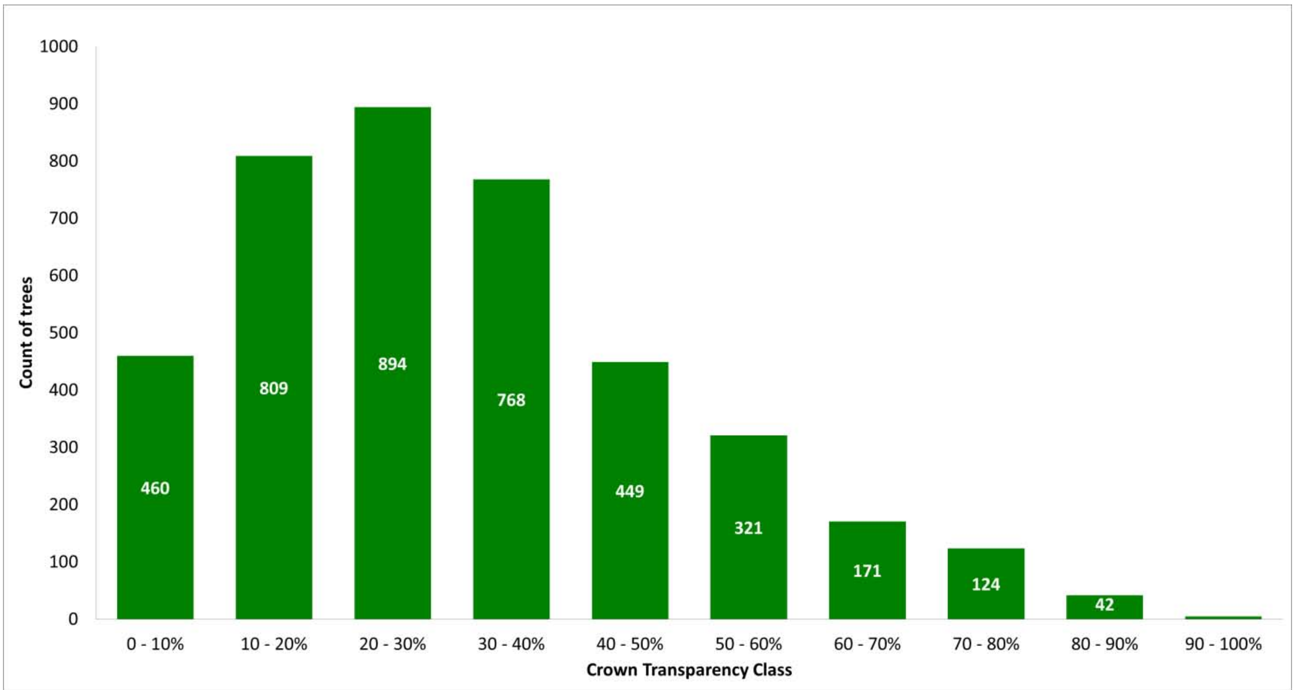


Figure 7. Histogram of crown transparency of top half of the crown for the trees in the 2010 survey

Crown transparency was found to be highly correlated using a Pearson's product-moment correlation with tree age for the entire crown (0.737) but less so when only the top half of the crown was assessed (0.504). Transparency was plotted against tree age and linear regression was used to describe the relationship between age and crown transparency. The strength of the relationship between transparency of the entire crown is of concern as changing age structure within the radiata pine resource will result in significant changes in the results for crown transparency even though crown transparency has not changed. Crown transparency of the top half of the crown only has a weaker relationship with tree age which suggests that this may be a more appropriate measure. This finding is analogous with that reached by Bulman (2008).

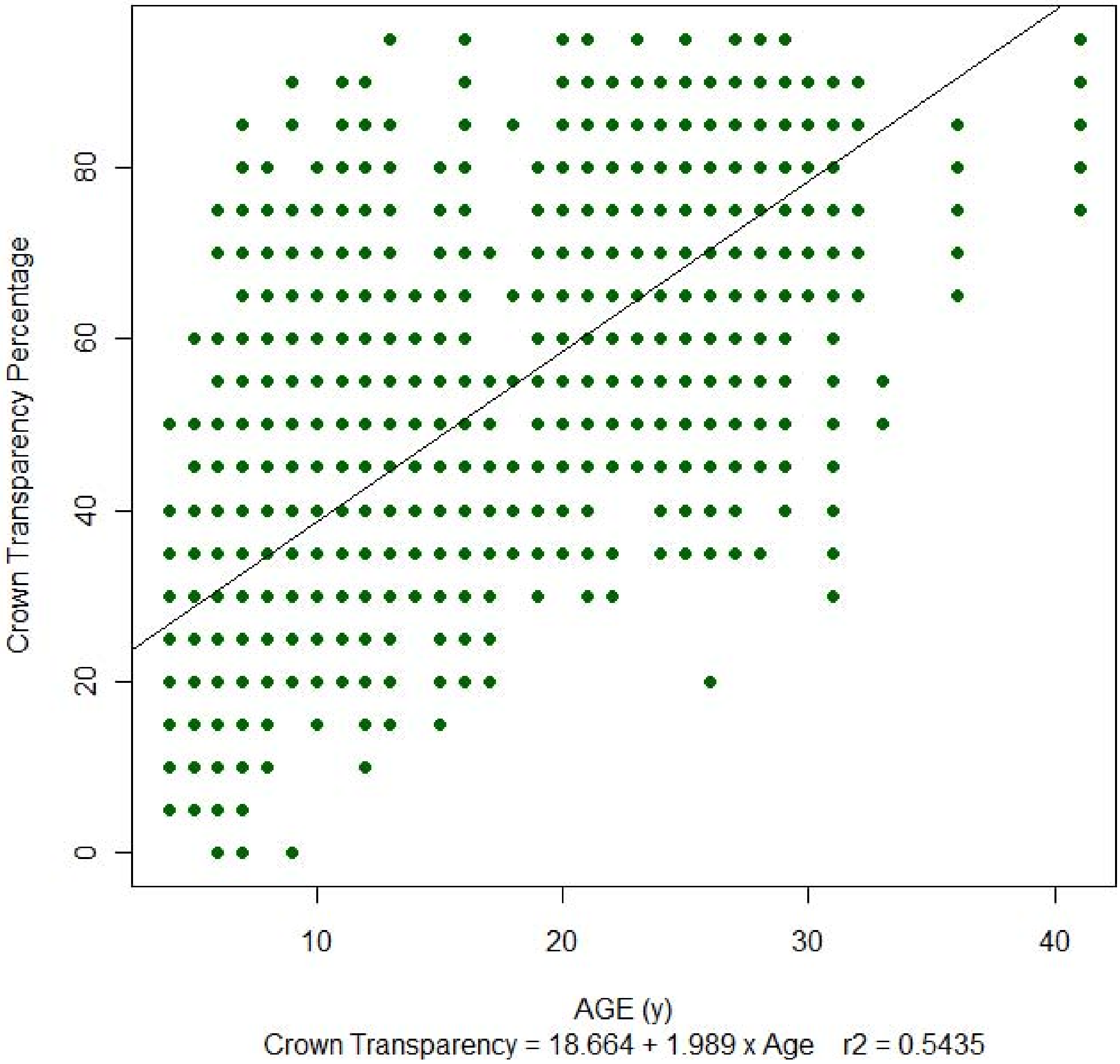


Figure 8. The relationship between age and transparency for assessment of the entire tree crown for trees in the 2010 survey

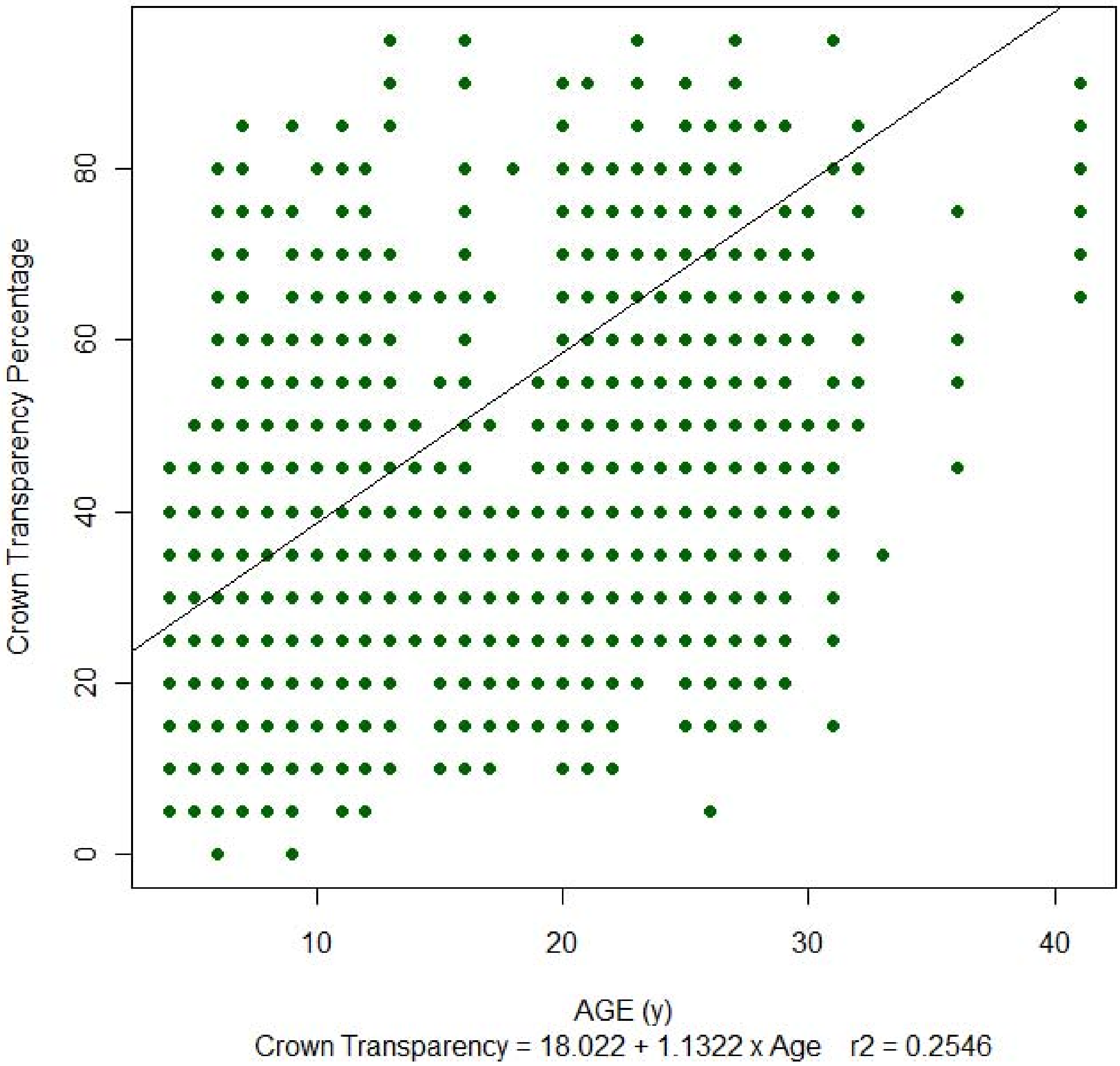


Figure 9. The relationship between age and transparency for assessment of the top half of tree crown for trees in the 2010 survey

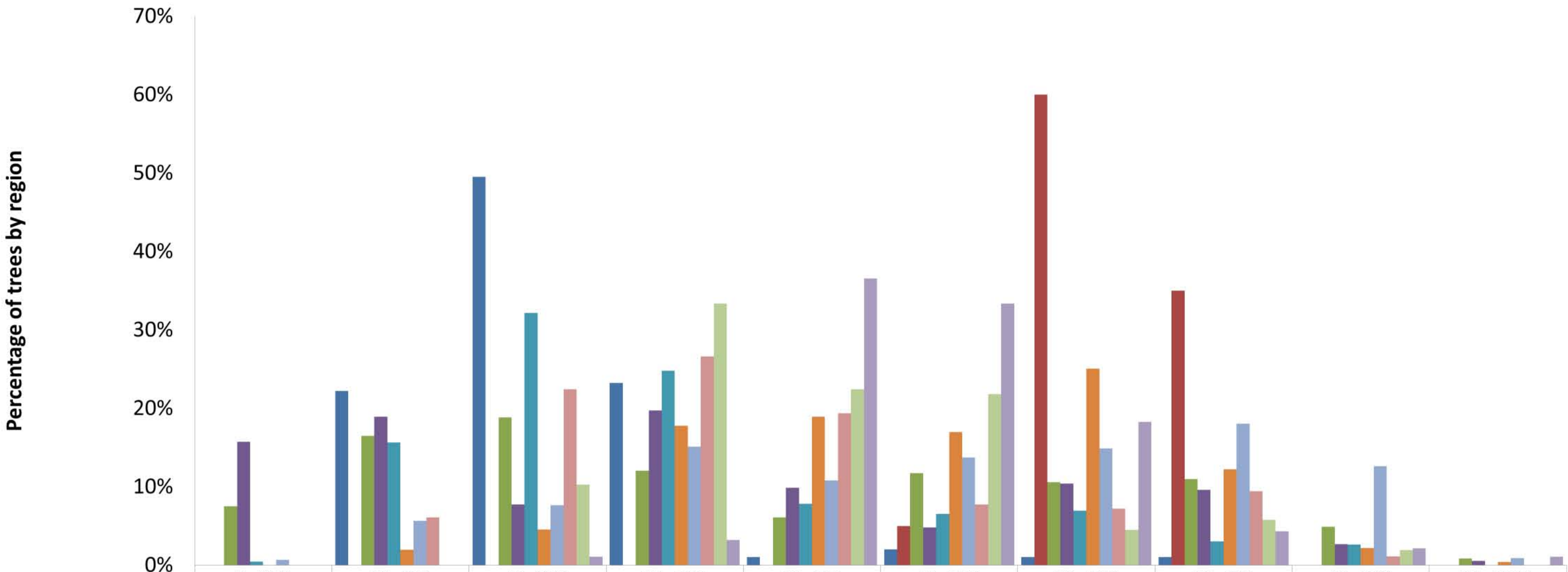
4.6 Geographic Distribution of Crown Transparency Results

Crown transparency data was collected in plots throughout the country and so some inference into spatial trends in the data may be drawn. The crown transparency data segregated by region is presented in this section but it must be noted that the sampling design for this survey was produced with the objective of providing summaries at the national level and so there may be insufficient plots to provide summaries at a regional level. The number of trees assessed in each region and the regional mean and median crown transparency scores are presented in Table 4.

Table 4. Descriptive statistics for the Crown transparency data collected from the 2010 FCM survey.

	Sample Size		**Mean**		**Standard Dev.**		**Variance**	
	Entire Crown	*Top Half*	*Entire Crown*	*Top Half*	*Entire Crown*	*Top Half*	*Entire Crown*	*Top Half*
Auckland	99	99	28.69	15.51	9.68	9.27	93.67	9.27
Canterbury	20	20	70.50	47.75	5.83	8.96	33.95	8.96
Central North Island	1758	1758	43.20	29.69	24.17	19.73	584.31	19.73
East Coast	375	375	38.87	28.35	23.96	18.39	574.18	18.39
Hawkes Bay	230	230	37.54	30.72	17.28	13.96	298.63	13.96
Nelson and Malborough	507	507	55.57	45.89	15.90	13.55	252.83	13.55
Northland	444	444	57.30	41.48	21.50	18.86	462.09	18.86
Otago and Southland	361	361	43.80	35.50	17.24	10.60	297.22	10.60
Southern North Island	156	156	47.31	28.91	13.56	12.99	184.00	12.99
West Coast	93	93	56.77	44.19	11.44	11.16	130.79	11.16

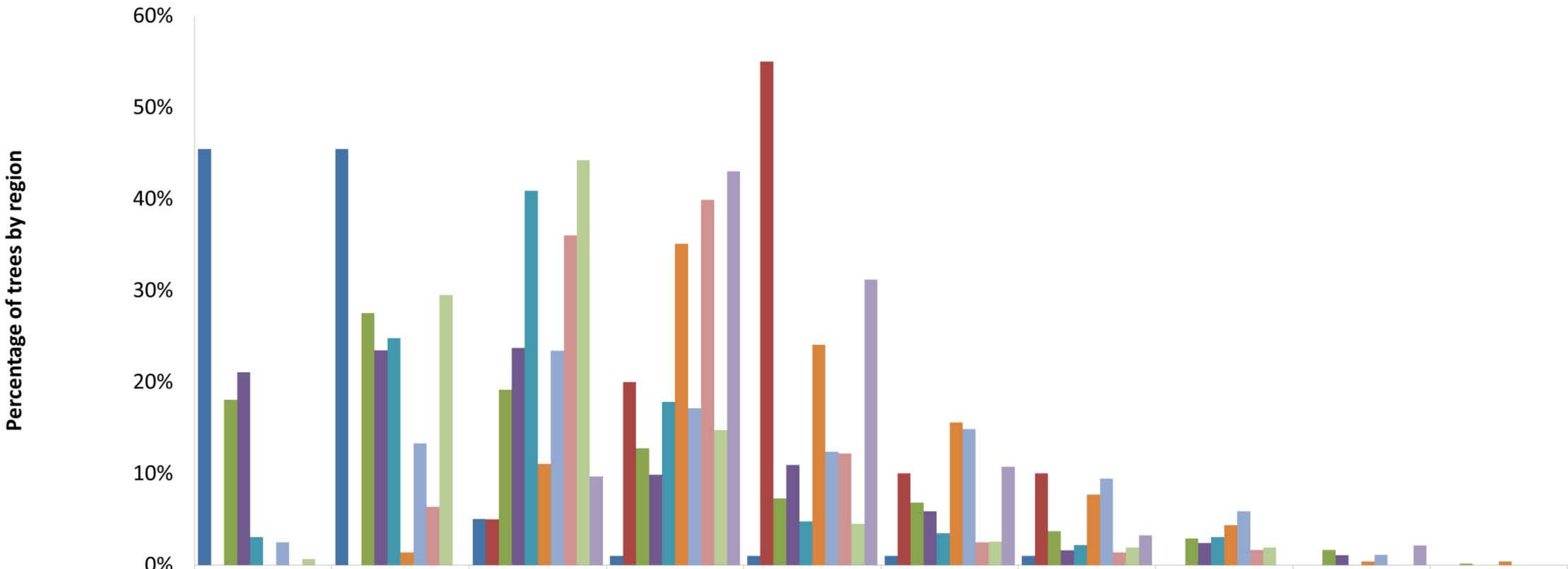
The percentage of trees in each crown transparency class by region is shown inFigure 1Figure 10 for the entire crown assessment and Figure 11 for the top half of the crown.



	0 - 10 %	10 - 20%	20 - 30%	30 - 40%	40 - 50%	50 - 60%	60 - 70%	70 - 80%	80 - 90%	90 - 100%
Auckland	0.00%	22.22%	49.49%	23.23%	1.01%	2.02%	1.01%	1.01%	0.00%	0.00%
Canterbury	0.00%	0.00%	0.00%	0.00%	0.00%	5.00%	60.00%	35.00%	0.00%	0.00%
Central North Island	7.51%	16.50%	18.83%	12.06%	6.09%	11.72%	10.58%	10.98%	4.89%	0.85%
East Coast	15.73%	18.93%	7.73%	19.73%	9.87%	4.80%	10.40%	9.60%	2.67%	0.53%
Hawkes Bay	0.43%	15.65%	32.17%	24.78%	7.83%	6.52%	6.96%	3.04%	2.61%	0.00%
Nelson and Malborough	0.00%	1.97%	4.54%	17.75%	18.93%	16.96%	25.05%	12.23%	2.17%	0.39%
Northland	0.68%	5.63%	7.66%	15.09%	10.81%	13.74%	14.86%	18.02%	12.61%	0.90%
Otago and Southland	0.00%	6.09%	22.44%	26.59%	19.39%	7.76%	7.20%	9.42%	1.11%	0.00%
Southern North Island	0.00%	0.00%	10.26%	33.33%	22.44%	21.79%	4.49%	5.77%	1.92%	0.00%
West Coast	0.00%	0.00%	1.08%	3.23%	36.56%	33.33%	18.28%	4.30%	2.15%	1.08%

Crown Transparency Class

Figure 10. Percentage of transparency of the entire crown for each region



	0 - 10%	10 - 20%	20 - 30%	30 - 40%	40 - 50%	50 - 60%	60 - 70%	70 - 80%	80 - 90%	90 - 100%
Auckland	45.45%	45.45%	5.05%	1.01%	1.01%	1.01%	1.01%	0.00%	0.00%	0.00%
Canterbury	0.00%	0.00%	5.00%	20.00%	55.00%	10.00%	10.00%	0.00%	0.00%	0.00%
Central North Island	18.03%	27.53%	19.17%	12.74%	7.28%	6.83%	3.70%	2.90%	1.65%	0.17%
East Coast	21.07%	23.47%	23.73%	9.87%	10.93%	5.87%	1.60%	2.40%	1.07%	0.00%
Hawkes Bay	3.04%	24.78%	40.87%	17.83%	4.78%	3.48%	2.17%	3.04%	0.00%	0.00%
Nelson and Malborough	0.00%	1.38%	11.05%	35.11%	24.06%	15.58%	7.69%	4.34%	0.39%	0.39%
Northland	2.48%	13.29%	23.42%	17.12%	12.39%	14.86%	9.46%	5.86%	1.13%	0.00%
Otago and Southland	0.00%	6.37%	36.01%	39.89%	12.19%	2.49%	1.39%	1.66%	0.00%	0.00%
Southern North Island	0.64%	29.49%	44.23%	14.74%	4.49%	2.56%	1.92%	1.92%	0.00%	0.00%
West Coast	0.00%	0.00%	9.68%	43.01%	31.18%	10.75%	3.23%	0.00%	2.15%	0.00%

Crown Transparency Class

Figure 11. Percentage of transparency of the top half of crown for each region

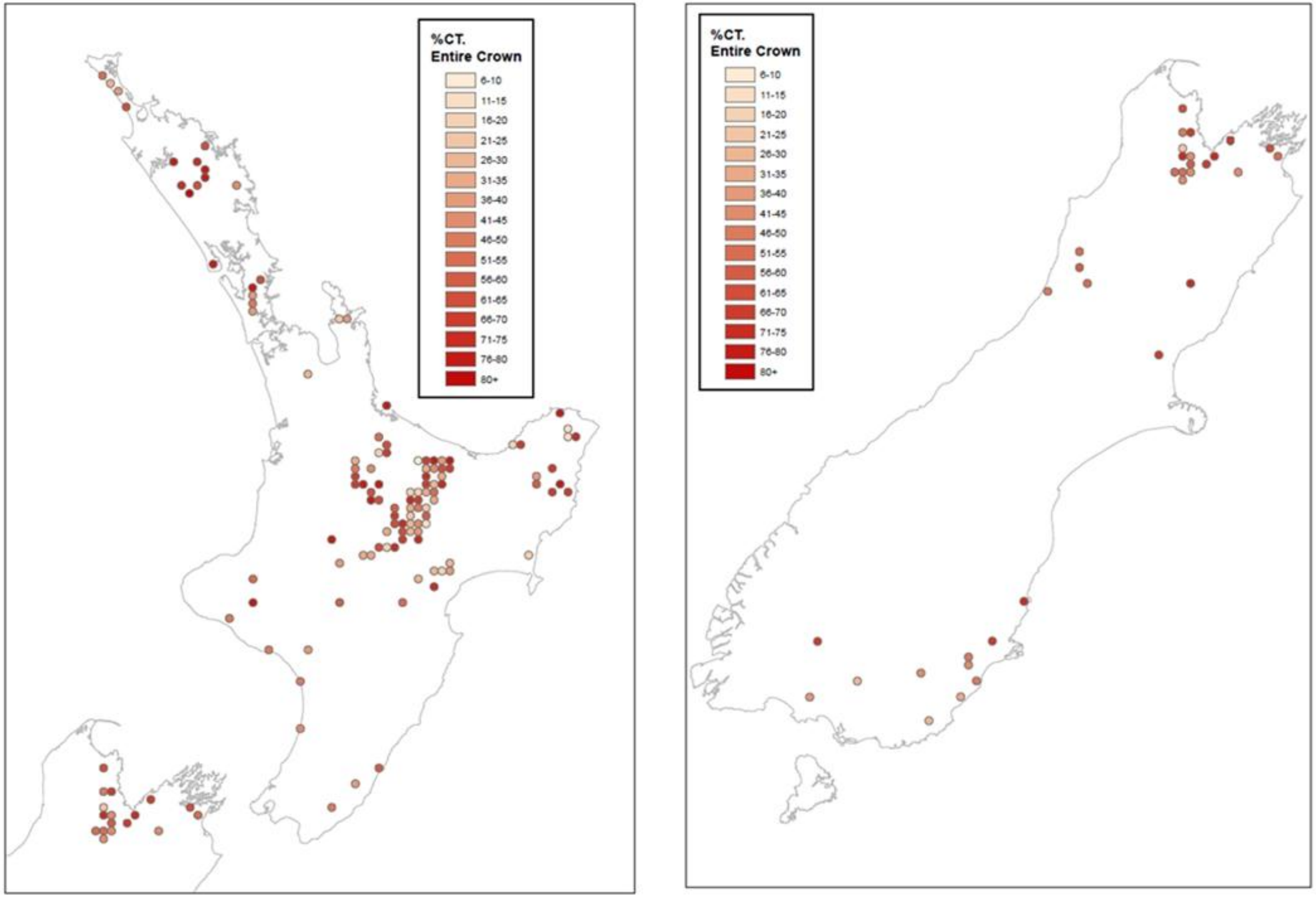


Figure 12. Patterns of crown transparency of the entire crown in the 2010 measurement of the FCM plot network

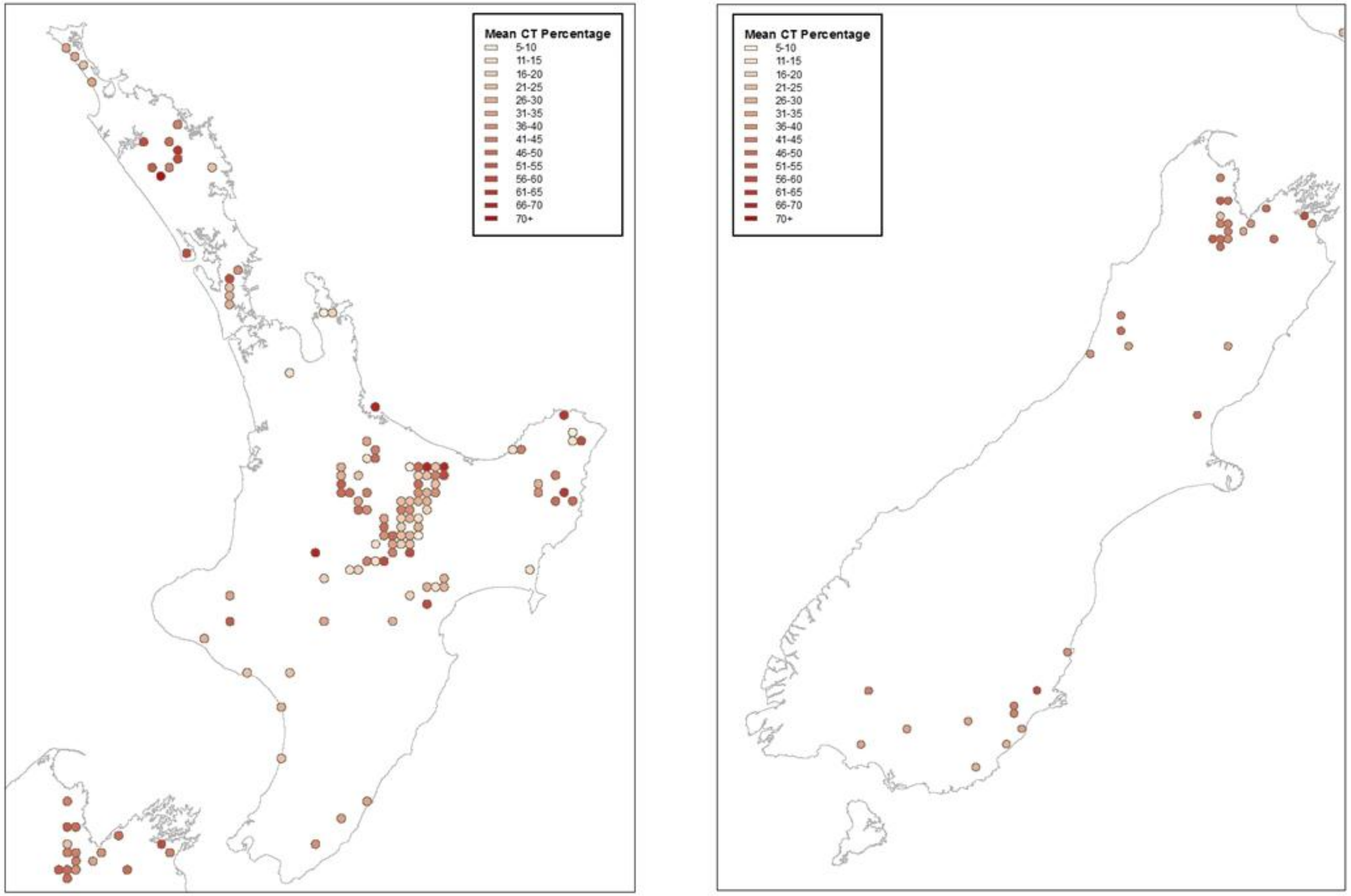


Figure 13. Patterns of crown transparency of the top half of the crown in the 2010 measurement of the FCM plot network

4.7 INDEPENDENT VARIABLES AFFECTING CROWN CONDITION

There are a large number of factors which may influence crown condition resulting in the patterns presented in the patterns present in the figures in section 4.3 – 4.6. These factors can be divided between those which affect individual trees (e.g. caused by genetic composition), site (e.g slope type or distance from the coast), or those which are common to groups of sites (e.g. most climatic factors or pollution deposition). To monitor these factors effectively a series of level 2 intensive monitoring plots would provide an ideal dataset for exploration of the causes of the crown condition patterns identified. However as this data is not yet available in New Zealand Interpine have acquired a variety of variables for use in the following analysis. There were two main sources for the independent variable datasets; the climatic, topographic and environmental surfaces available through the Land Resource Information Systems (LRIS) Portal[3] provided by Landcare Research and supplementary data collected as part of the MfE's Land Use and Carbon Accounting System (LUCAS) planted forest survey.

Multiple regression and its associated correlation analysis provide a robust and widely accepted method for determining whether an association exists between two variables. However many of the variables used may be intercorrelated which means that even if a significant association is found between an explanatory variable and a crown condition parameter this does not necessarily imply that there is a functional relationship between the variables. Similarly the reverse is true, no significant statistical relationship does not imply with absolute certainty that there is no functional relationship (Innes and Boswell 1987).

4.7.1 Independent data from LRIS Portal Data

Interpine acquired shape files containing surfaces for New Zealand made available through the LRIS portal which aims to make government and publicly funded science data readily available in human and machine readable formats. Interpine intersected these surfaces with a shape file containing the locations of the 2010 FCM survey plots to create a dataset for analysis of the relationships between the crown condition indicators and the independent datasets. The data acquired by Interpine for analysis includes:

- Mean annual temperature;
- Annual solar radiation;
- Soil temperature regime;
- Soil classification;
- Slope;
- Soil drainage class;
- Chemical limitations to plant growth;
- Salinity;
- Reserve potassium;
- Phosphate retention.

4.7.2 Independent data from LUCAS Survey

A large set of complimentary variables were collected during the measurement of the LUCAS surveys and have been acquired by Interpine for use in this analysis. These factors include:

[3] http://lris.scinfo.org.nz/#

- Altitude;
- Slope;
- Physiography;
- Aspect;
- Soil carbon content;
- Soil nitrogen content;
- Tree diameter at breast height;
- Tree height.

4.8 CORRELATION ANALYSIS

Simple correlation and regression analysis was used to investigate the response in the key FCM variables to a range of explanatory variables. All analysis reported on in this section was undertaken in the R statistical computing environment and unless otherwise stated a Pearson correlation test was used to explore the relationships. The correlation between the measured tree indices and the explanatory variables investigated are given in Figures 14 – 16.

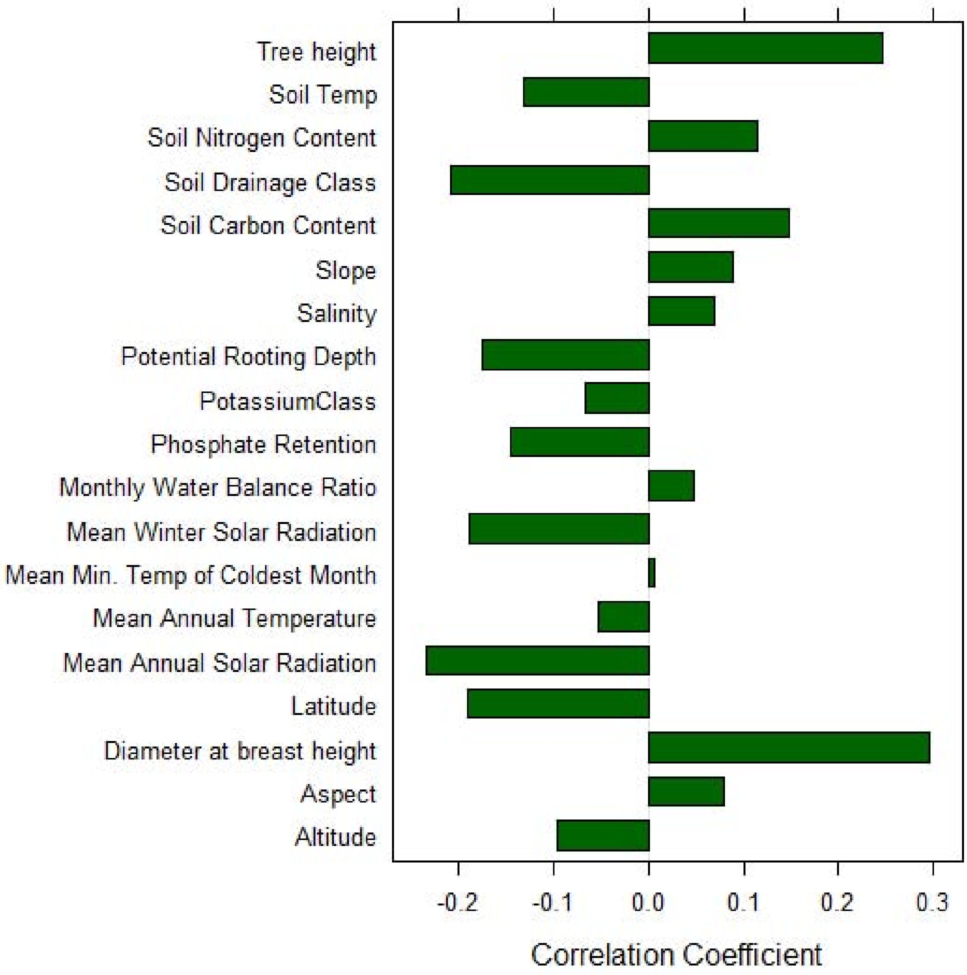


Figure 14. The correlation matrix produced for the defoliation variable

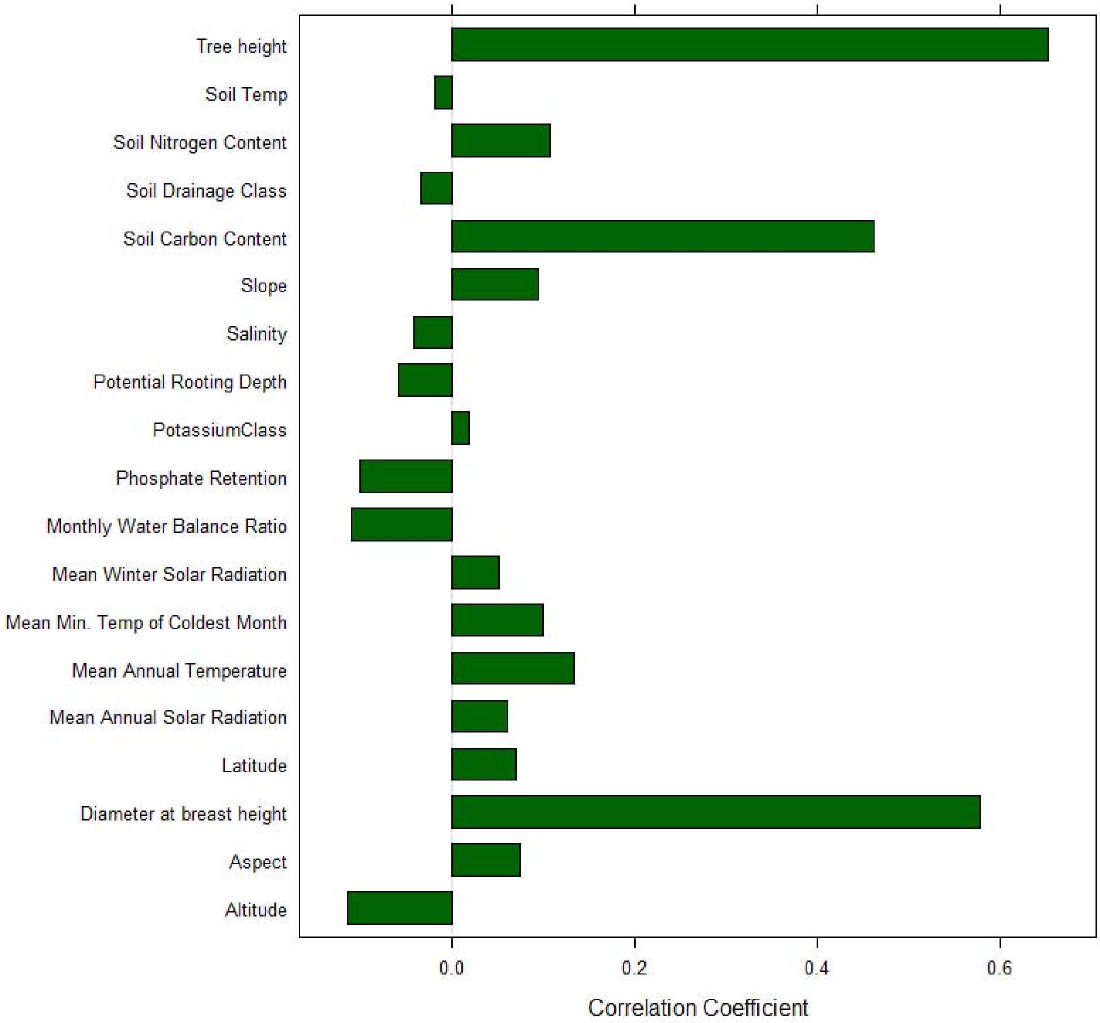


Figure 15. The correlation matrix produced for the transparency of the entire crown variable

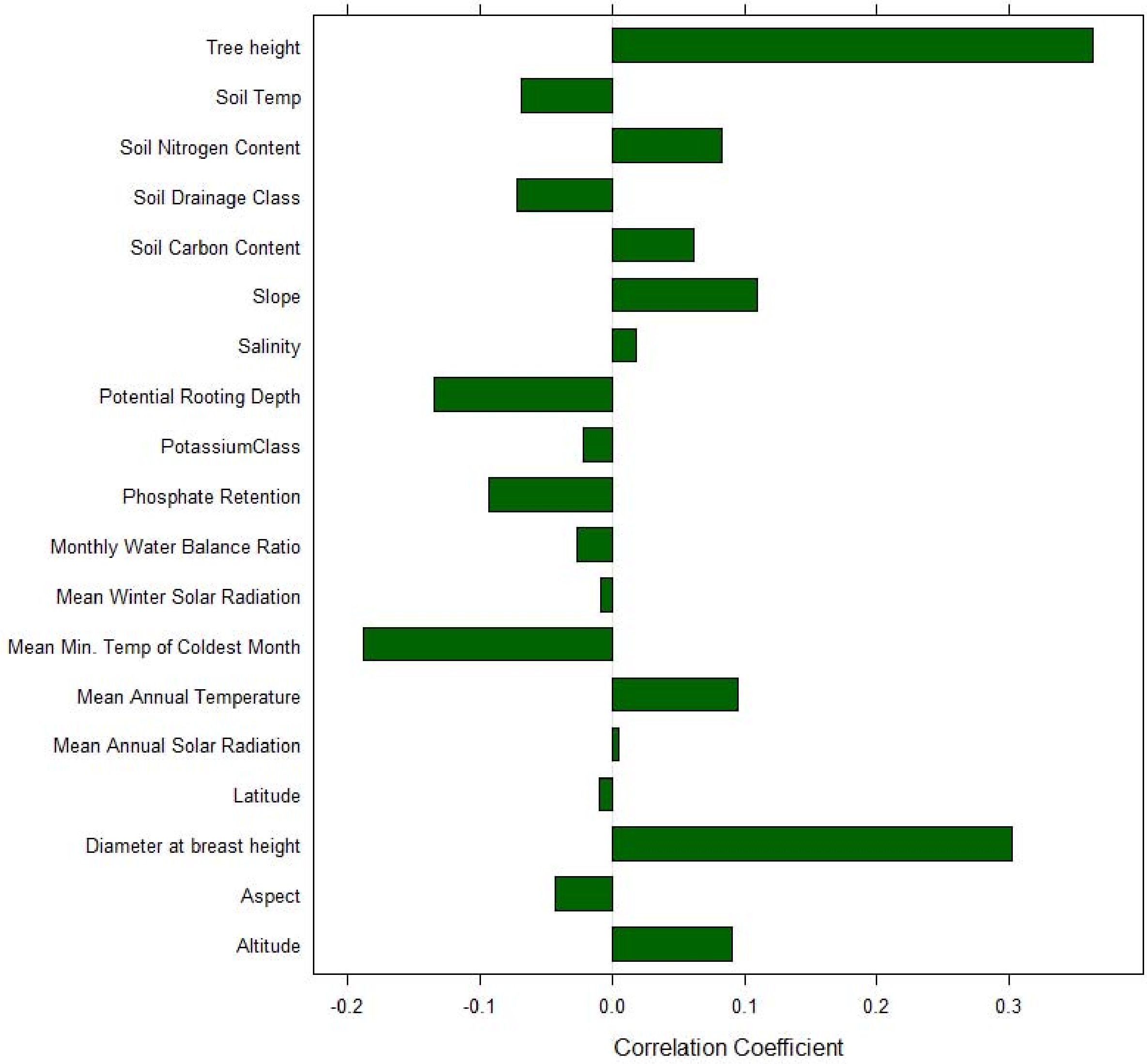


Figure 16. The correlation matrix produced for the transparency of the top half of the crown variable

4.9 Adjusting for Age Effect in Crown Condition Assessments

When assessing crown condition an independent annual sample can be used in which case the change in crown condition can be assessed as the difference in the mean observed crown condition between the two samples. When data are assessed on the same trees over time the change in crown condition must be treated as a single variable. This is advantageous because the variance in the single variable is lower than the pooled variance of the two variables used to determine the mean change between independent samples; resulting in a more precise estimate of the mean (Wonnacott and Wonnacott 1977). A certain decline in crown condition can be expected over time as the subject tree ages and this must be accounted for during analysis. The methodology reported on here provides a framework for adjusting crown condition assessments for the effect of age.

The expected change in crown condition due to aging must be modelled empirically from the relationship between observed crown condition and age in a sample taken during a single year. The purpose of the modelling exercise is to find an equation relating crown condition to age. This can then be used to determine the change in condition due to a change in tree age (Strand 1994). The relationship between crown condition and age has been described earlier in this report by regressing crown condition against age using least square regression. Using the methodology set out by Strand (1994) once the coefficients have been derived from the regression analysis the expected change in crown condition can be found using the equation:

$$\Delta v = f(\Delta a)$$

Where: Δv = expected change in crown condition;

Δa= change in age;

$f(\cdot)$ =a function derived from the regression equation.

As a linear regression model was used to describe the relationship between condition and age $f(\cdot)$ simply amounts to multiplying Δc with the slope of the regression line. The age adjusted change in crown condition can be calculated using the following equation:

$$x = c_{t2} - c_{t1} - \Delta v$$

Where: x= age adjusted change in crown condition;

c_{t2} and c_{t1} are the observed crown condition in years t_1 and t_2.

The age adjusted change in crown condition is the unexplained change in crown condition once the change associated with ageing has been removed. The age adjusted change in crown condition in a healthy forest should approach zero.

5 Discussion

The results presented in this document provide a useful summary of the geographic spread of the main crown condition indicators assessed in 2010.

The defoliation status of 4043 live radiate trees was assessed in 2010, a defoliation classification system was developed which enables the segregation of trees into four classes based on the defoliation score produced. This classification is based on internationally accepted biological thresholds and will provide a sound basis for comparison for defoliation scores in future measurement years. The defoliation assessment data collected in 2010 indicates that only 4.3% of trees were damaged (defoliation score of more the 25%) with the remainder showing no or only slight defoliation.

A good sample of trees was established from the majority of regions in New Zealand with the exception of the Canterbury region which was represented by only 20 trees in two plots. Unsurprisingly the majority of plots were focussed in regions with the greatest proportion of planted forest estate notable the Central North Island and Nelson and Marlborough. Plots with higher defoliation scores were focussed in central Northland whereas plots in the Central North Island showed little evidence of defoliation.

Crown transparency (CT) was also assessed 4043 trees across New Zealand in 2010 and two definitions of the assessable crown area were used for assessment. CT was found to be higher on average when assessed over the entire crown compared to the top half of the crown. This reflects the fact that the lower sections of the crown exhibiting suppression from neighbouring trees are included in this assessment area. All trees exhibited some degree of transparency and the both CT of the entire crown and the upper crown were found to be strongly correlated with tree age with the entire crown exhibiting the stronger correlation. This finding indicates that upper crown transparency may be a more reliable crown condition indicator than entire crown transparency.

An analysis of the geographical spread of CT scores shows that trees in the Auckland and Southland areas tended to be the least transparent for both the entire crown and the upper crown measures.

5.1.1 Correlation Analysis

The relationship between the crown condition indicators, defoliation and transparency, with a series of explanatory variables was investigated using a correlation analysis approach. Explanatory variable data was obtained from Landcare Research's LRIS portal and also from the independent data collected and stored as part of the LUCAS planted forest inventory programme. Using a spatial join in Geographical Information System (GIS) software the specific plot values for the explanatory variables were extracted for each plot and used to derive correlation matrices which detail the correlation coefficient for each variable. The results of this analysis are discussed in the following section.

Defoliation

The correlation matrix for defoliation (Figure 14) shows that defoliation has a weak negative relationship with mean annual radiation this means that sites with more annual solar radiation tend to be less defoliated. A similar strength negative relationship is evident with soil drainage class indicating that trees growing on less well drained sites are more defoliated. This is concurrent with the growth pattern of radiata pine which is known to exhibit decreased vigour in poorly drained soils. A moderate strength positive relationship was found between defoliation and both tree height and diameter at breast height. This suggests that larger trees are more defoliated than smaller trees; this is consistent with the expected degradation of tree condition as trees grow and age. It should be noted that none of the relationships between defoliation and the explanatory variables were strong (>0.5).

Transparency of entire crown

The correlation matrix for the transparency of the entire crown Figure 15 displays a strong relationship between DBH and tree height and therefore the fact that larger trees are more transparent is readily apparent. The only other explanatory variable which is strongly correlated with crown transparency is Soil carbon content. This outcome indicates that trees on sites containing more carbon tend to be more transparent. This finding seems to be counterintuitive but it is possible that soil carbon content is affected by the age of the tree crop in a specific site as soil carbon may accumulate during the course of a rotation due to the build-up of detritus. None of the other explanatory variables had a significant relationship with the transparency of the entire crown.

Transparency of the Upper Crown

Similarly to transparency of the entire crown the correlation matrix for the transparency of the upper crown (Figure 16) displays a medium strength correlation with DBH and tree height indicating that the upper crowns of larger trees are more transparent. All other relationships with the explanatory variables investigated are trivial with the exception of the mean minimum temperature of the coldest month. This variable displays a moderate negative relationship with upper crown transparency indicating that the upper crown of trees growing in areas with colder winters are more transparent.

Conclusion

No strong relationships were found between crown condition and any of the independent explanatory variables investigated. This result suggests that either that the explanatory factors used were not of sufficient quality and spatial resolution or that the explanatory variables affecting crown condition have not yet been investigated. Both of these conclusions are feasible, in Europe a series of intensive monitoring plots are established which are often spatially concurrent with the crown condition monitoring plot network. These plots facilitate the collection of detailed climatic and ecosystem process measurements which are spatially and temporally coincident with the crown condition data.

It should also be noted that no data relating to pollutant or nutrient deposition, and plant and pathogen distribution on the crown condition plots was available for this study. Studies elsewhere in the world have found that pollution deposition is a major factor in crown condition and data relating to this could prove a useful explanatory variable for future work on crown condition.

5.1.2 Adjusting for age effect

It has been identified that several crown condition indicators, notably crown transparency, are strongly correlated with tree age. This means that if the age structure of the national resource changes then there will be a change in crown condition despite the fact that there is no change in tree condition. This is highly problematic for forest condition monitoring schemes as it may provide an inaccurate impression of forest condition change. Section 4.9 details a methodology which can be used to mitigate the effect of age using a function which includes the regression coefficients which describe the relationship between crown condition and tree age.

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