RADIATA PINE CROWN DEVELOPMENT:
Model, model performance, and Incorporation into Forest inventory

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EXECUTIVE SUMMARY

A model predicting crown development in radiata pine (*Pinus* radiata D. Don) has been developed by destructively sampling 49 trees from eight different regions within New Zealand. This has been linked with an individual-tree distance-independent growth model to create the model “TreeBLOSSIM”. As with any model, it is important to provide evidence that TreeBLOSSIM provides realistic predictions across a wide range of sites, silvicultural treatments and improved seedlots.

Model performance in predicting the number of branch clusters and branch diameter for a wide range of independent sites has been examined by comparing model predictions with data collected from photographic or digital images using a non-destructive, ground-based photogrammetric method, TreeD. This exercise has highlighted that stem damage is a common occurrence at some sites and has a major influence on the branching characteristics of radiata pine, resulting in larger than expected branch diameters.

Research is underway to create a link between the function predicting the number of branch clusters in an annual shoot and a field count of branch clusters within a nominated stem section collected during routine forest inventory. This will allow TreeBLOSSIM be adapted for specific sites and seedlots (branch cluster frequency is a selection criterion in radiata pine breeding programmes), and thus provide more realistic estimates of yield by log-types to be obtained from forest inventory data.

RADIATA PINE CROWN DEVELOPMENT: MODEL, MODEL PERFORMANCE, AND INCORPORATION INTO FOREST INVENTORY

Jennifer C. Grace

INTRODUCTION

Radiata pine (*Pinus radiata* D. Don) is the main commercial forestry species grown in New Zealand, covering 1.6 million ha within a land area of 26.9 million hectares (New Zealand Forest Owners Association, 2006). New Zealand covers a wide range of environmental conditions and early research indicated that there were significant differences in the patterns of radiata pine growth across the country. To account for this variation in growth between different environments, a decision was made to develop separate stand-level growth models for seven different radiata pine growing regions: Auckland Clays, North Island Sands, Central North Island, Hawke's Bay, Nelson, Canterbury and Southland, see Figure 1 (Goulding, 1994). More recently, Leathwick *et al.* (2003) have developed the Land Environments of New Zealand (LENZ), an environmental classification of New Zealand utilising 15 environmental variables (7 climatic, 7 soil and 1 landform). There are four levels of detail containing 20,100, 200, or 500 environments. This provides an alternative, quantitative, method for classifying sites that warrants investigation in the development of future growth models.

Since the late 1980s, most forest management research has been funded jointly by the New Zealand Government and the forest industry through research cooperatives such as the Stand Growth Modelling Cooperative (www.ensisjv.com). One of the projects supported by the Stand Growth Modelling Cooperative has been the development of models to grow inventory data collected at mid-rotation, after silviculture has been completed, forward in time to the end of the rotation so that rotation-end log yields from different cutting strategies may be predicted (Gordon *et al.* 2006). Variables recorded during inventory include tree DBH, tree height, and visual estimates of stem form and the diameter of the largest branch for different sections of the stem. As inventory data are collected on individual trees without the precise location of the trees being recorded, a distance – independent modeling approach was considered appropriate. Individual tree - distance independent growth models to predict height, diameter at breast height (DBH) and tree mortality (R.G. Shula, unpublished) have been developed for the above seven growth modeling regions. A model was developed for an 8th region, Westland, but further validation indicated it was more appropriate to use the model for the Nelson region. The forms of the equations are analogous to those used by Wykoff *et al.* (1982). In addition to the tree growth models, regional branch growth models, that link with the tree growth models, have been developed to allow the estimated branch diameters to be grown forward in time (Grace et al. 1998, Grace et al. 1999, Grace, 2004). The combined model is known as TreeBLOSSIM. These components are also incorporated in commercially available ATLAS Technology software (www.atlastech.co.nz).

The branching component of TreeBLOSSIM is hierarchical in structure. At the tree level, it predicts the probability that the tree will form stem cones. At the annual shoot level, it predicts the number of branch clusters formed and their relative position within the annual shoot. At the cluster level it predicts the number of stem cones and branches formed. At the branch level, it predicts the change in branch diameter through time, the age when the branch dies (the branch knot becomes bark encased) and whether there will be bark trapped above the branch. Data to develop the model functions were obtained by felling near-rotation age trees (see Grace *et al.* 1998) for further details. In addition to addressing the needs of forest inventory, the model contains sufficient detail to create a link to sawing simulators such as AUTOSAW (e.g. Todoroki, 1990). A simulation study, linking this branch model to AUTOSAW indicated that the number of branch clusters in an annual shoot and number of branches were the most important branching variables influencing value when boards are visually graded (Pont *et al*., 1999).

As well as regional differences in radiata pine growth, the species is genetically variable. This variability has been exploited in the tree breeding programme that has been in place since the 1950's. This has developed different "breeds" of radiata pine including the "Growth and Form Breed" where the aim was to produce trees with fast growth, and excellent form; and the "Long Internode Breed" where the aim was to produce knot-free wood from unpruned trees (Jayawickrama and Carson (2000). This later breed, in particular, has exploited the fact that there is genetic variability in the number of branch clusters formed annually. A seed certification scheme was established in 1987 to provide a "Growth and Form (GF) rating for seedlots. This has since been replaced with GFPlus™ that gives individual trait ratings for growth, straightness, branch cluster frequency, resistance to *Dothistoma*, wood density and spiral grain.

To provide data for future model development, the Stand Growth Modelling Cooperative established trials across the above growth modeling regions and, where appropriate, different site qualities (low site index, medium site index, high site index, and high basal area) within each region. Each trial contains permanent sample plots (PSPs) of radiata pine with a range of different GF ratings and different silvicultural treatments, but the seedlots and silvicultural treatments have varied with year of establishment. Most of the PSPs have been thinned to waste at a mean crop height of 6.2 m to give a final crop stocking ranging from 100 stems/ha to 600 stems/ha, which spans the final crop stocking in previously proposed silvicultural regimes proposed for radiata pine (James, 1990).

The forest industry needs to have confidence in model predictions. Model predictions for two of the more important branching components of TreeBLOSSIM have been compared to measurements collected using a non-destructive, photogrammetric image-based system in several of the above trials and other permanent sample plots suggested by industry. This provides evidence for where the model performance is satisfactory and where further data collection is required. The original system, PhotoMARVL (Firth *et al.* 2000) used a film camera and photogrammetic work station for data collection. Subsequently the system was modified to use a digital camera and computer and was renamed TreeD (Brownlie *et al.* 2007). The name TreeD is used subsequently regardless of whether the data was collected using a film camera or a digital camera. TreeD is a two-phase system. In the first phase, a vertical pole is hung from the sample tree to provide a reference. From a distance of 15 – 20 m, a pair of images are then taken separated by a horizontal distance of about 1m, and seven field parameters associated with the tree collected. In the second phase the field parameters are used to register the images in the computer to enable the tree to be viewed in stereo. The dimensions of any feature visible on the tree stem (to approximately 20 m in height) can be measured and the feature's position recorded in 3-dimensional space. TreeD has several advantages. It avoids felling trees, is quicker than climbing, and more importantly, provides a permanent record which can be revisited when required. TreeD images show one side of the tree, but unless the largest branch in the cluster is growing in the same direction as that between the tree and where the image is taken, the largest branch should be visible in the image.

The objectives of this paper are to discuss current knowledge on the number of branch clusters and the diameter of the largest branch in a cluster gained through the development and validation of TreeBLOSSIM, and how we suggest the model is combined with inventory procedures.

TreeBLOSSIM VERSION 3.1

Data to develop the branching component of TreeBLOSSIM have been obtained from felling selected trees and then measuring their branching characteristics. The large number of measurements required for a single tree, has limited the number of sample trees. For example a mature radiata pine tree may have over 100 branch clusters and up to 15 branches and /or stem cones in a cluster. Initial data collections were from trees classified as GF7, but most of the recent data collections have been from trees classified as GF14. TreeBLOSSIM Version 3.1 has been developed using data collected on 49 GF14 trees from 9 sites covering 8 growth modeling regions (Table 1). The data collection methodology is outlined in Grace *et al.* (1998). Sample trees were selected to avoid any obvious stem malformations such as leader changes. Occasionally leader changes were observed on the felled stem. These were noted, and annual shoots containing these leader changes were excluded from the analysis, as they were not considered representative of the “normal” branching pattern.

Number of branch clusters in an annual shoot

Radiata pine forms several branch clusters within a year. Bannister (1962) recorded a maximum of 6 clusters. For the current GF14 dataset of 646 annual shoots, a maximum of 8 clusters was recorded. The number of branch clusters in an annual shoot is currently predicted as a function of annual shoot length and tree age when the annual shoot was formed. The number of branch clusters in an annual shoot is influenced by site / environment (Bollmann and Sweet, 1976), hence a separate function was derived for each dataset.

Branch diameter

Branch diameter, adjacent to the stem, increases rapidly for a number of years and then remains approximately constant. Branch diameter in radiata pine is influenced by many factors, and this has been modelled using a series of multiplicative “potentials” that determine the maximum diameter that a branch may reach. These potentials allow branch diameter to be influenced by region, stocking, relative tree size within the plot, relative cluster size within the tree, and relative branch size within the cluster. There is also a response variable that allows the branch potential to be modified as a result of thinning. Actual branch diameter is predicted as a function of tree age and its “potential”.

TreeBLOSSIM PERFORMANCE

Methods

TreeD has been used as a tool to determine how well TreeBLOSSIM predicts the number of branch clusters and the diameter of the largest branch in a cluster across a wide range of site conditions, silvicultural treatments and different genetically improved seedlots. To date, TreeD data have been collected from 19 trials managed by the Stand Growth Modelling Cooperative (Table 2). In each trial, a range of silvicultural treatments and/or seedlots were assessed, and in total measurements are available for:

- 259 trees from 54 PSPs with a GF rating of 14,
- 193 trees from 35 PSPs with a GF rating between 21 and 25,
- 134 trees from 25 PSPs containing long internode seedlots with a long internode rating between 19 and 28.

In each PSP, sample trees were selected in the office to span the range of tree DBH within the plot and avoid trees where stem damage had been noted.

TreeD Image analysis

The following measurements were extracted from the images:

- stem diameter below the cluster,
- height to base and top of the cluster,
- diameter of the largest branch in the cluster that was visible on the image (*BDI)*.

TreeBLOSSIM simulations

For each selected sample plot, the most recent PSP measurements were imported into Version 3.1 of TreeBLOSSIM. Any mortality that had occurred in the PSP was accounted for by assuming a thinning at that age. This approach allowed the actual stocking of the plot to be maintained. The branching pattern was then estimated for each tree, and then (where necessary) the plot grown forward to the age at which the images were taken.

Comparisons

For each tree, the TreeBLOSSIM branching pattern for the section of stem measured by TreeD was extracted. The position of each cluster and the diameter of the largest branch in that cluster (*BDTB)* were retained.

The data for each tree was then summarised to give:

- BDI_{max} The maximum branch diameter measured on the TreeD image (i.e. maximum value of *BDI* for the tree)
- $BDTB_{max}$ The maximum branch diameter predicted by TreeBLOSSIM for that stem section (i.e. the maximum value of *BDTB* for the stem section)

- BDI_{av} The mean branch diameter measured by TreeD (i.e. average value of *BDI* for the tree)
- $BDTB_{av}$ The mean branch diameter predicted by TreeBLOSSIM for that stem section (i.e. average diameter *BDTB* for the stem section)
- *CLI* Number of branch clusters on the stem section measured by TreeD
- *CLTB* Number of branch clusters on the **same** stem sections in the TreeBLOSSIM prediction
- *zonelength* Height to base of highest cluster – height to base of lowest cluster, both measured from the image

The following differences were then calculated for each tree:

- $DIFF_{av} = BDI_{av} - BDTB_{av}$
- $DIFF_{max} = BDI_{max} - BDTB_{max}$
- $DIFF_{CL} = (CLI - CLTB) / zonelength$

Criteria were set for deciding whether TreeBLOSSIM produced realistic results for each tree. These were:

- Abs($DIFF_{av}$) ≤ 20 mm
- Abs ($DIFF_{max}$) ≤ 20 mm
- Abs ($DIFF_{CL}$) ≤ 0.33 clusters/metre

The first two criteria were based on the fact that TreeD measures branch diameters to within ±10 mm when the images are taken approximately 15 m away from the sample tree (Brownlie *et al.*, 2007), and an estimated acceptable error for TreeBLOSSIM predictions of ± 10 mm. The 3rd criterion allows for TreeBLOSSIM predictions of number of branch clusters to be out by 1 cluster over 3 m and on average equates to less than 1 cluster per annual shoot given that the mean annual shoot length for the 9 destructively sampled sites varied between 1.2 and 2.0 m.

RESULTS

TreeD images have been collected for individual trees in Permanent Sample Plots (PSPs) managed by the Stand Growth Modelling Cooperative:

- 259 trees from 54 PSPs with a GF rating of 14,
- 193 trees from 35 PSPs with a GF rating between 21 and 25,
- 134 trees from 25 PSPs containing long internode seedlots with a long internode rating between 19 and 28.

For each of the above three group of trees, bar-charts were plotted showing the values $DIFF_{av}$, $DIFF_{max}$ and $DIFF_{CL}$. The zero bar on each graph shows the percentage of trees that fall within the above criteria, i.e. the percentage of trees for which TreeBLOSSIM predictions are considered realistic. Each bar is sub-divided by growth modelling region as an aid to identifying areas where model performance is acceptable and where further improvements to TreeBLOSSIM are required (Figures 2-5).

$DIFF_{av}$

$DIFF_{av}$ within the set criterion for 85% of the GF14 trees, 77% of the GF20+ trees and 53% of the long internode trees (Figure 2). $DIFF_{av}$ was positive for the remainder of the long internode trees, and indicates that the long internode seedlots tended to have larger branches compared to the G14 seedlot. The results for the GF20+ trees were similar to those for the GF14 trees.

$DIFF_{max}$

$DIFF_{max}$ was within the set criterion for 54% of the GF14 trees, 51% of the GF20+ trees, and 34% of the long internode trees (Figure 3). $DIFF_{max}$ was between 20 mm and 60 mm for a large proportion of the remaining trees. There were a few trees where $DIFF_{max}$ was greater than 60 mm and the images for such trees were re-examined. The large values could be attributed to some form of stem damage such as a leader replacement / steeply angled branches, or a tree growing in a large gap for at least 14 of the 20 GF14 trees, 18 of the 24 GF20+ trees, and 12 of the 22 long internode trees. Such trees tended to be from PSPs where the nominal final stocking was 100 and 200 stems/ha (Figure 4). In general, TreeBLOSSIM tended to predict smaller branches than observed for trees where the nominal final stocking was 100 or 200 stems/ha. (Figure 4). The predicted variation in branch diameters between clusters was higher than observed for several GF14 trees in the Sands region and this contributed to the negative values of $DIFF_{max}$.

$DIFF_{CL}$

$DIFF_{CL}$ was within the set criterion for 48% of the GF14 trees, 58% of the GF20+ trees and 31% of the long internode trees (Figure 5). There were differences in the distributions between the 3 seedlots, and these differences indicate that the GF20+ seedlots tend to have more branch clusters than the GF14 trees, aand that the long internode trees tend to have fewer branch clusters than the GF14 trees. This is to be expected given that long internode seedlots were designed to have fewer branch clusters than GF14 seedlots. There were some obvious regional effects. For example, $DIFF_{CL}$ was negative for all trees from the Sands region, and generally positive got the GF14 trees from Southland and GF20+ trees from Nelson.

LINKING INVENTORY DATA with TreeBLOSSIM

Branch diameter

Branch diameter is often an important characteristic for determining log quality, and, during a forest inventory, a tree stem is visually classified into lengths according to a given set of maximum branch diameters, i.e. each stem length has an associated branch class. Some typical values of maximum branch diameters that may be used are 4 cm, 7 cm, 10 cm, and 15 cm.

One approach to linking these inventory assessments of branch diameters with TreeBLOSSIM is as follows. Use TreeBLOSSIM to estimate the branching pattern for each individual tree, and then, where necessary adjust branch potentials so that the diameter of the largest branch in a cluster is in general agreement with the nominated branch classes. Care needs to be taken when deriving the rules for adjustment as the inventory data may not record every minor change in branch class, and in some instances the decrease in branch diameter in the growing crown may not be recorded. A set of rules is implemented in the Atlas Cruiser software. One positive aspect of inventory data is that it will identify the unusually large branches that are often underpredicted by TreeBLOSSIM. The combination of inventory data and TreeBLOSSIM predictions provides a realistic description of the branching pattern of the tree, including the position of unusually large branches, which may be grown forward in time to the required age.

Number of branch clusters in an annual shoot

The position of branch clusters is only measured in a few forest inventories. For situations where branch cluster positions have not been measured, the possibility of predicting number of branch clusters from environmental variables has been investigated using the Land Environments of New Zealand (Leathwick *et al.*, 2003). Where a field count of branch clusters is available, a method of using these data to estimate the number of branch clusters in an annual shoot has been investigated. For both analyses, data on number of branch clusters in an annual shoot was revisited.

Within TreeBLOSSIM, the number of branch clusters in annual shoot is currently predicted as a function of annual shoot length and tree age when the annual shoot was formed, i.e. incorporates the effects of year-to-year variation in annual shoot length due to environmental conditions. However, height growth models in TreeBLOSSIM are not driven by environmental variables, and only predict average trends in height growth. A possible alternative is to ignore the relationship between annual shoot length and clusters per year, and investigate the relationship between number of branch clusters in an annual shoot and tree age when the annual shoot was formed.

Analyses indicated that there was no significant correlation at a tree level between number of branch clusters in an annual shoot and tree age when the annual shoot was formed. At a site level there was no significant correlation between the mean number of clusters in an annual shoot for an individual tree and tree DBH at the time of felling.

The tree values for mean number of branch clusters in an annual shoot were averaged to give a site mean. The relationship between these site means and environmental variables available through LENZ was examined. The site mean values for number of branch clusters in an annual shoot was correlated ($p< 0.05$) with latitude and 5 of the 17 LENZ environmental variables (Figure 6):

- Annual temperature (°C) – monthly mean daily temperature, averaged across all onths.
- Winter minimum temperature (°C) – mean daily minimum temperature of the coldest month, usually July.
- Annual solar radiation ($MJ/m^2/day$) – monthly mean daily solar radiation, averaged across all months.
- Winter solar radiation ($MJ/m^2/day$) – mean daily solar radiation in June.
- Phosphorus – analysis of sub-soil concentration using half-molar sulphuric acid and a five-step scale.

There was a general trend for the number of branch clusters in an annual shoot to increase with increasing temperature and increasing solar radiation, but decrease with increasing phosphorus. A relationship between the number of branch clusters in an annual shoot and one or more of these variables will be included in the next release of TreeBLOSSIM for evaluation using the above TreeD data sets.

Where branch clusters are counted during an inventory, the variables recorded are: a cluster count, and the height of the lowest and highest cluster included in a count. For example the lowest 10 clusters may be considered. The tree age at each height may then be estimated using the height growth equations, and then the average number of branch clusters in an annual shoot estimated. This approach will be included in the next release of ATLAS Cruiser for testing.

DISCUSSION

Modelling is an iterative process consisting of data collection, model development and model testing. Destructively sampled datasets for developing this branch model have been collected at the rate of approximately one a year. The current version of TreeBLOSSIM (Version 3.1), which was designed for GF14 seedlots, has been built using data from 9 sites, covering 8 regions (Table 1). The number of sites is low due to the number of measurements taken on each tree. For example a mature radiata pine tree may have over 100 branch clusters and up to 15 branches and /or stem cones in a cluster.

Given the low number of sample sites, and the known variability in site quality within a region, it is very important to determine how well the model will perform over a much wider range of site qualities and silvicultural conditions. This approach allows forest managers to see how TreeBLOSSIM performs for their forests and also provides ideas for the next iteration of TreeBLOSSIM.

TreeBLOSSIM (Version 3.1) predictions have been compared with branching data collected using reasonably quick (quicker than climbing) non-destructive photogrammetric procedure called TreeD (Brownlie *et.al.* (2007). The TreeD data set for GF14 seedlots covered 17 region × site quality combinations as opposed to 8 in the destructively sampled dataset (Table 2). In addition, the performance of TreeBLOSSIM has been examined for 12 region × site quality combinations where the GF rating is between 21 and 25; and for 7 region × site quality combinations where long internode seedlots have been established (Table 2).

Three criteria were used as a guide as to whether TreeBLOSSIM predictions were reasonable. The performance of the model across a far wider range of site and silvicultural conditions is considered to be very promising, given the very limited dataset used to develop the model.

In terms of “average branch diameter”, TreeBLOSSIM predictions are good with 85% of the GF14 trees falling within the defined acceptable limits. The performance was similar for the GF20+ seedlots, but noticeably poorer for the long internode seedlots.

In terms of “maximum branch diameter”, TreeBLOSSIM predictions were good for 54% of the GF 14 trees. The performance was similar for the GF20+ seedlots but noticeably poorer for the long internode seedlots. There were a few trees for which TreeBLOSSIM overpredicted branch diameters, and was the result of the variation in branch diameters being larger than observed. Improvements to this function need to be investigated for the next version of TreeBLOSSIM.

Two issues, not currently included in TreeBLOSSIM, were identified when examining trees where TreeBLOSSIM underpredicted branch diameters. One issue was stem damage, where the following scenario appears to occur. If a tree loses it leader / top, then branches compete to become the new leader, resulting in large-diameter steeply angled branches. The diameter of such branches are under-predicted by TreeBLOSSIM. The second issue was that branch diameters were under-predicted where there was a large gap on one or more sides of the tree. This indicates that branch diameter growth is influenced by the available space in the direction the branch is growing. This fact that has previously been noted for shelterbelts (Tombleson and Inglis, 1988) was recently observed in a PSP with a nominal stocking of 200 stems/ha where the trees had been planted at a spacing of 11.3 m × 4 m. This fact may also be influencing the performance of TreeBLOSSIM for trees with a nominal final crop stocking of 500 stems/ha. These PSPs were planted at 5 m × 4 m (a 5 m square spacing corresponds to a nominal stocking of 400 stems/ha) and left unthinned, and fewer trees fell within the acceptable limits compared to PSPs with a nominal final crop stocking of 400 or 600 stems /ha (Figure 4).

In terms of “number of branch clusters”, TreeBLOSSIM predictions were reasonable for 48% of the GF14 trees, but there was a tendency for TreeBLOSSIM to predict more clusters than observed, in particular for the Sands growth modeling region (Figure 5). The reason for this is not known and should be determined by destructively sampling some of the trees measured using TreeD before the stand is clearfelled. TreeBLOSSIM predictions were slightly better for the GF20+ seedlots, and indicate that the GF20+ seedlots have more branch clusters than the GF14 seedlots. TreeBLOSSIM, as expected, predicted more branch clusters than observed for the long internode seedlots.

Methods have been described to incorporate inventory assessments of branch diameter into TreeBLOSSIM. Users should have confidence in TreeBLOSSIM predictions of future branch diameter for GF14 and GF20+ trees, given that the above analyses indicated that TreeBLOSSIM gave acceptable predictions for the majority of GF14 and GF20+ trees, and the only major issue was predicting odd extremely large branches, but these will have been noted in the inventory data. TreeBLOSSIM tended to underpredict branch diameters for long internode trees. If

TreeBLOSSIM is used to grow long internode branch diameters forward in time then one of the following is suggested: collect branch data using TreeD or use very small branch zones (say 2 cm) when collecting inventory data. These approaches will avoid TreeBLOSSIM underpredicting the initial branch diameters.

Two methods have been described to improve the estimates predicted number of branch clusters in TreeBLOSSIM. One approach, to be used at inventory, involves counting the number of branch clusters between two heights and will be applicable for all seedlots. The other approach involves predicting the number of branch clusters from environmental variables and is only appropriate for GF14 seedlots, because the number of branch clusters in an annual shoot has been shown to vary between seedlots. Further destructive sampling would be needed to develop appropriate relationships with environmental variables for other breeds.

Future Developments

TreeD has proved a useful tool for determining the performance of TreeBLOSSIM. The TreeD data base needs to be expanded so that we have at least one dataset per growth modeling region × site quality and /or Land environment for comparing with current and future versions of TreeBLOSSIM. An additional function in TreeBLOSSIM to predict the likelihood of stem damage would be a useful addition in order to mimic future stem damage. Additional destructively sampled datasets are required to improve the TreeBLOSSIM model itself. Branch growth data needs to be collected for some large steeply-angled branches that have been formed as a result of stem damage to determine whether their growth patterns fit the previously measured trends. Priority areas for future data collections are GF14 data in the Sands growth modeling region and long internode data in any area. In the latest studies, wood property information have been collected in addition to branching data and will be used to investigate the influence of branching on wood property distributions, particularly circumferentially around the stem.

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Table 1. Destructively sampled GF 14 trees used in the development of TreeBLOSSIM.

Region	Site Quality	Latitude (º)	Nominal initial stems/ha	Nominal final stems/ha	Number of trees
North Island Sands	Medium SI	36.5	800	400	8
Auckand Clays	High SI	36.7	1878	250	5
Central North Island	Medium SI	38.3	625	400/200/100	3
Central North Island	Medium SI	38.5	800	400	8
Hawke's Bay	Medium SI	39.3	621	100	3
Nelson	Low SI	41.6	625	400/200/100	3
West Coast	Medium SI	42.5	800	400	8
Canterbury	Low SI	43.5	625	400/200/100	3
Southland	Low SI	46.2	800	400	8

Table 2. TreeD datasets compared with TreeBLOSSIM predictions.

Region	Site Quality	Nominal final stems/ha	Seedlots
Clays	Medium SI	200, 400, 600	GF14, GF25, LI25
Clays	High SI	200, 400	GF14, GF25
Clays	High BA	200, 400, 500, 600	GF14, GF22, LI23
Sands	Low SI	300	GF14, GF22
Sands	Medium SI	100, 200, 400, 625	GF14
Central North Island	Medium SI	100, 200, 400, 625	GF14
Central North Island	Medium SI	200, 400, 500, 600	GF14, GF21, LI28
Central North Island	High SI	300	GF14, GF22
East Coast	High BA	100, 200, 400, 600	GF14, GF25
Hawkes Bay	Low SI	100, 200, 400, 600	GF14, GF25, LI25
Hawkes Bay	High BA	300	GF14, GF22
Hawkes Bay	High BA	200, 400, 500, 600	GF14, GF21, LI28
Nelson	Low SI	100, 200, 400, 625	GF14
Nelson	Medium SI	300	GF14, GF22
Nelson	High SI	100, 200, 400, 625	GF14, GF25, LI25
Canterbury	Low SI	100, 200, 400, 625	GF14
Canterbury	Medium SI	300	GF14
Southland	Medium SI	300	GF14, LI19
Southland	High BA	300	GF14, GF22

Figure 1. Map of New Zealand showing the growth modeling regions.

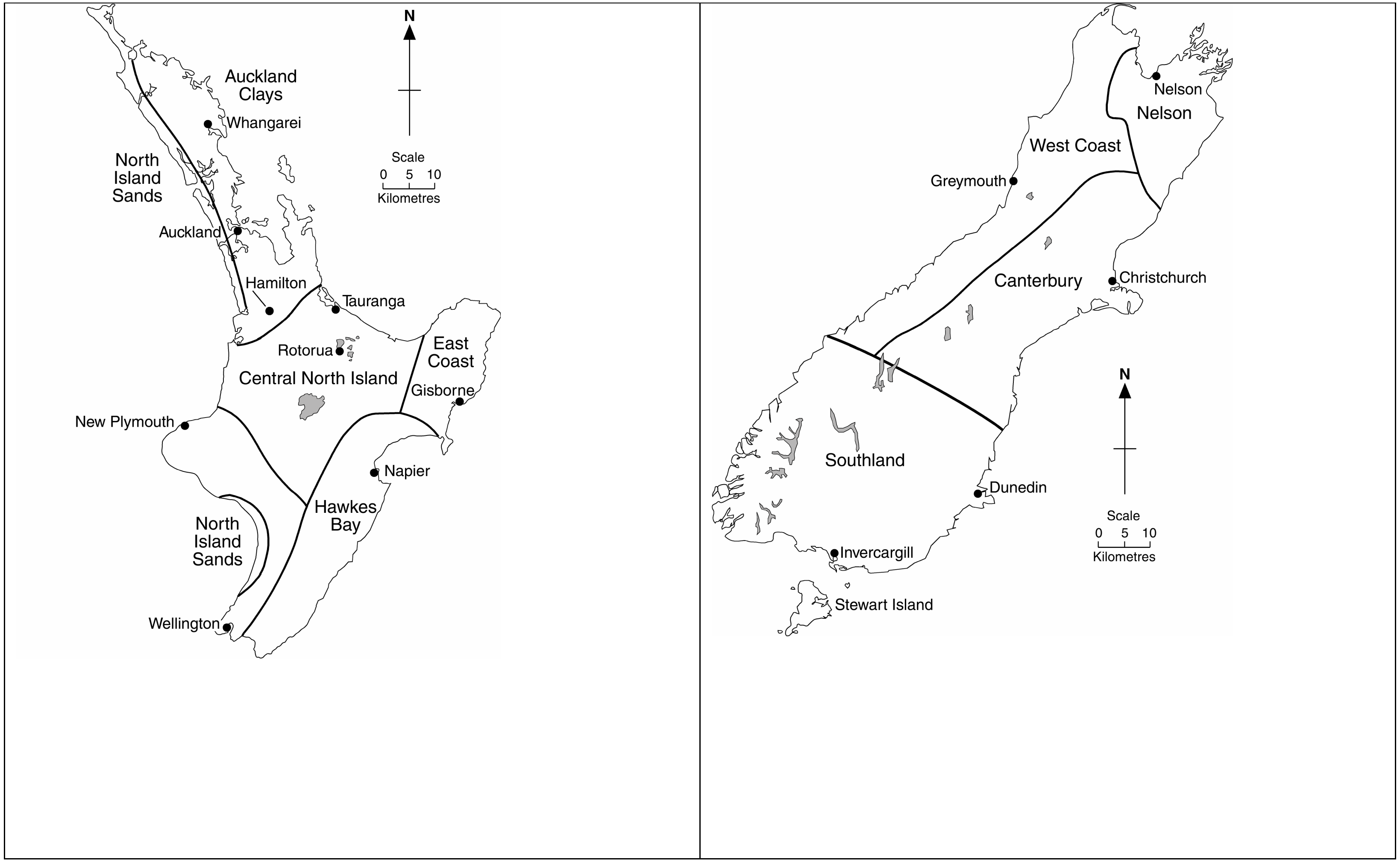

Figure 2. Distribution of individual tree values of $DIFF_{av}$ for GF14, GF20+ and long internode seedlots. (Bars coloured according to growth modeling region)

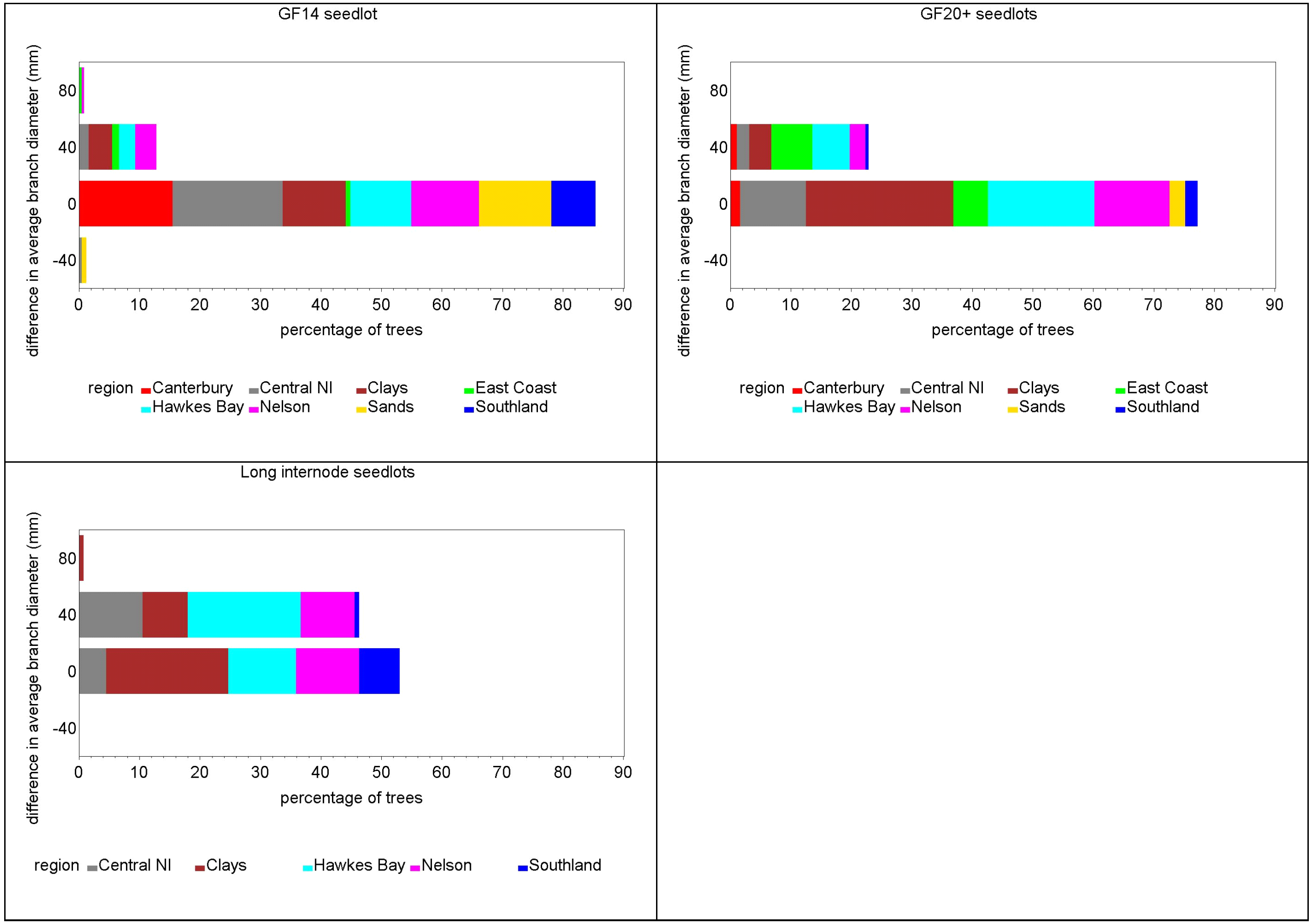

Figure 3. Distribution of individual tree values of $DIFF_{max}$ for GF14, GF20+ and long internode seedlots. (Bars coloured according to growth modeling region).

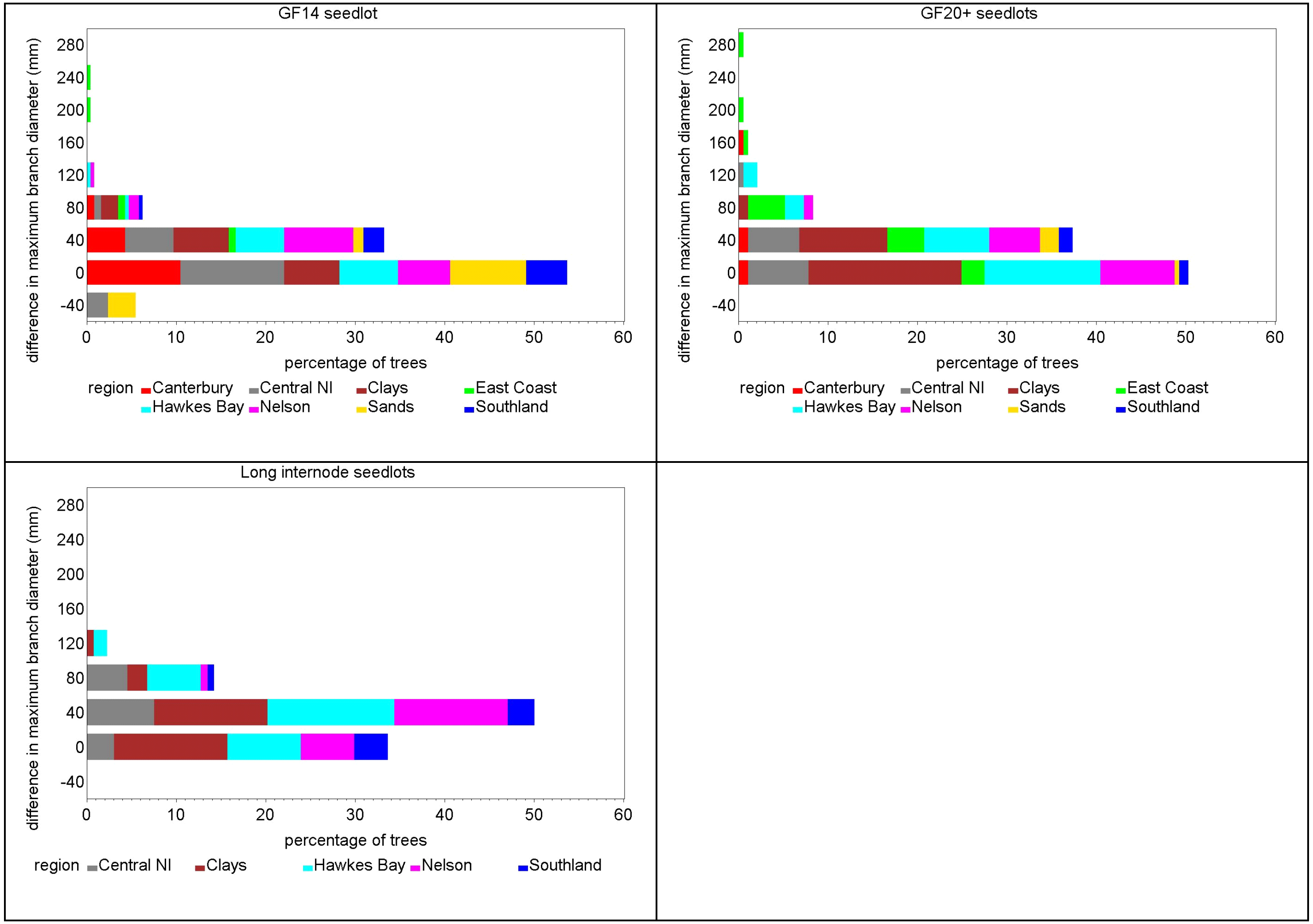

Figure 4. Distribution of individual tree values of $DIFF_{max}$ for GF14, GF20+ and long internode seedlots. (Bars coloured according to nominal final crop stocking).

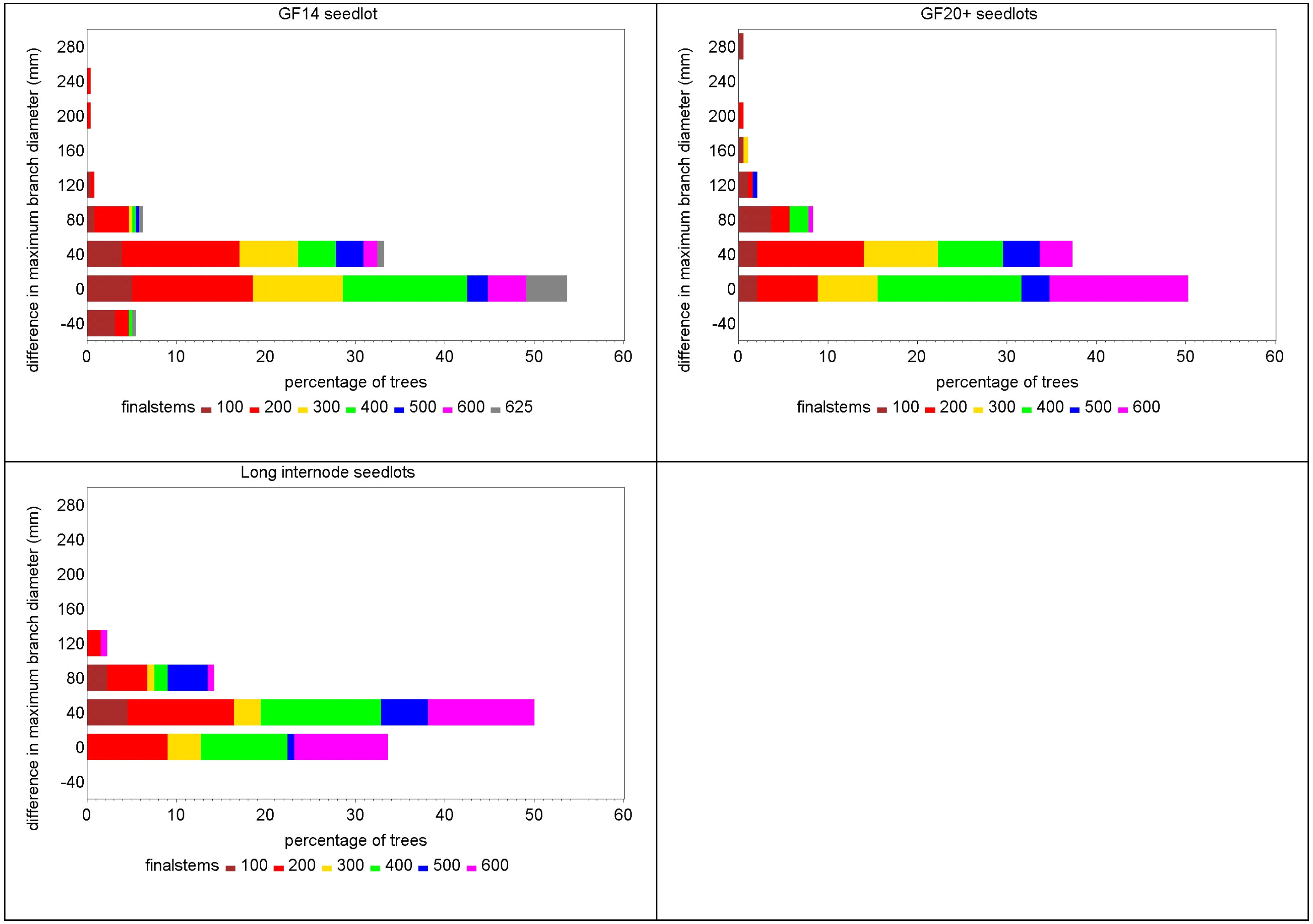

Figure 5. Distribution of individual tree values of $DIFF_{CL}$ for GF14, GF20+ and long internode seedlots. (Bars coloured according to growth modeling region).

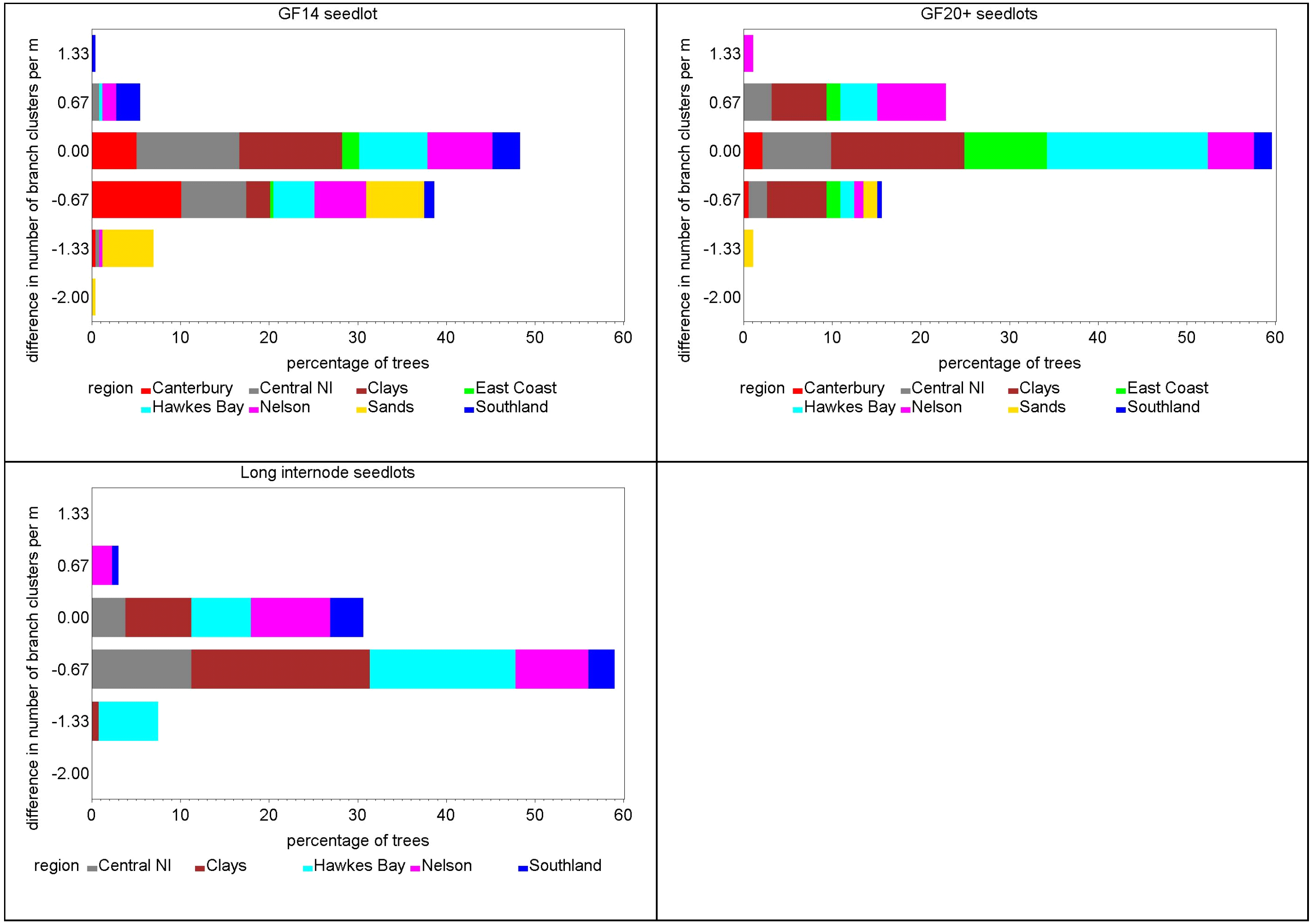

Figure 6. Bar charts how the percentage distribution for number of branch clusters in an annual shoot vary with environmental conditions.