PO Box 1127
Rotorua 3040
Ph: + 64 7 921 1883
Fax: + 64 7 921 1020
Email: info@ffr.co.nz
Web: www.ffr.co.nz

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Validation of the WQI spiral grain model

Roderick D. Ball and Dave J. Cown

Scion (New Zealand Forest Research Institute Limited)

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EXECUTIVE SUMMARY

The WQI spiral grain models derived from the Benchmarking data (samples from a total of 150 trees from 17 sites of the 1978 Genetic Gains Trial) were compared for fit with other historic data.

Major findings were:

- The WQI models behave in a logical manner, in that they predict a general decrease in spiral grain with ring number from the pith.
- However, the WQI models did not fit all 17 Benchmarking sites equally well. Coefficients of determination ranged from about 10% to 60%. Significant differences of around 5 degrees were found for some sites. Separate model fits and a linear mixed model fit showed that model coefficients vary substantially between sites, i.e., *one model does not fit all*.
- Known patterns of variation in spiral grain within the juvenile wood zone could not be accounted for because of the sampling method adopted by WQI. The variables used (density, growth rate, distance from the pith and temperature) are associated with spiral grain in this dataset, but have not been proven to be causal.
- When validated against historic data from Tikitere, predictions were consistently and significantly low. The adjusted WQI model performed reasonably well at the butt level only, but predicted a steeper decline in spiral grain with ring number than observed. Differences further up the stem (5, 10, 15, and 20m) were substantial (over 5 degrees). When validated against data from Forsyth Downs (4 stockings), the WQI models consistently over-predicted by over 5 degrees.
- The WQI modes are descriptive of the average trends in a particular study, and should not be adopted without a better understanding of site and tree-level variability.
- The recommended approach for modelling spiral grain in conjunction with growth models is to use the known generic patterns of radial and vertical variation, and include effects such as growth rate (e.g. thinning) and genotype only after confirmation with robust data and appropriate statistical models and tests. It is recommended that mixed non-linear or smoothing spline models be used for this purpose in future.
- The WQI model is based on a GF 14 seedlot, and work to date on families is inconclusive (limited to 3 trees per family over 18 families). It is recommended that the database be further built to study effects of silviculture and genotypes, in particular modern seedlots and clones.

BACKGROUND

We were asked to validate models for spiral grain developed for WQI by University of Canterbury School of Forestry (WQI report No. Res 35 by E. Mason and H. Dzierzon). The models were derived from the WQI Benchmarking data (Cown *et al.* 2005; consisting of samples from 17 sites of the 1978 Genetic Gains Trial; averaging 9–10 trees per site). Grain angles were measured from disc samples at ring numbers, 5, 10, 15, 20, and 25. The sampling strategy was designed to confirm known trends and to document environmental effects.

The coefficients for the model are presented in Tables 13 and 14 of the report "Radiata pine resource characterisation" (WQI report No. Res 35 by E. Mason and H. Dzierzon). Table 13 of the WQI report is reproduced as Table 1. There was a transcription error in the WQI Res 35 Table 14 coefficients. Table 2 contains the amended coefficients. (E. Mason pers. comm.).

We were advised that the model is 'more descriptive than predictive' — the model was intended to describe the relationships in the WQI data. The authors did not intend the model to be used for prediction on all future forests in New Zealand.

METHODS

Methods used in the WQI report:

Data: The data for the WQI model consists of spiral grain and densitometry data from 17 sites (the WQI 'National benchmarking study').

Models: Two models are presented. One with density (WQI Res35: Table 13) and one without density but with temperature instead (WQI Res 35: Table 14). Each of the WQI models is a single linear regression model fitted to all data.

This model ignores site, tree and disc effects, and assumes that individual ring measurements are independent. (The assumptions of the linear regression methodology are that model errors are independent, identically distributed random variables.) *Such assumptions are extremely naive in the present context, and if violated, all tests, inferences or predictions from the WQI model are invalid.*

Our experience in Scion is that these assumptions do not hold, on the contrary there are strong within-tree trends and differences between sites and genotypes for spiral grain and other wood properties that need to be understood. These trends and dependencies are apparent in the WQI and validation data (cf. results section). Scion has developed statistical methods and software to model this variation

Use of 5-ring blocks: The WQI data and model were limited to averages of 5-ring blocks, because of the use of terms (*radius* and *radial growth rate* defined as the average distance from the pith or ring width respectively for a block) calculated from 5-ring blocks. This can obscure details of the pattern of spiral grain variation.

Nevertheless, the WQI models developed on 5-ring blocks could be applied to individual ring data. When this was done, comparable results were obtained, albeit with a reduction in R^2 from about 40% to about 30%. This reduction is not unexpected given the higher variability of individual ring data, and the inability of 5-ring data to show the micro-trends in spiral grain.

Model choice: There are many possible models that could be fitted and many were tried, although only the finally selected models are documented in the report. In an attempt to avoid problems due to the nature of the model, significance levels were increased and a mixed model was also used (E. Mason pers. comm.).

These *ad hoc* adjustments do not guarantee strong evidence for selected covariates or that all important covariates have been found, or that significance of effects are not artefacts of non-linearity in spiral grain trends.

Residual plots: residual plots at the ring level such as Res 35: Figure 19 can, but do not necessarily, show departures from the model in the presence of hierarchical structure such as site, tree, and disc random effects. Our plots do show systematic departures from the model (Figures 1–3).

Validation method used:

We have adjusted the sign of predictions from the WQI model to conform to the standard that a left hand spiral (grain sloping to the left when looking up the tree) is positive.[1]

Note: In addition to the difference in sign conventions, there was a transcription error in the WQI Res 35 Table 14 coefficients (E. Mason pers. comm.). We have used corrected values for WQI Res 35 Table 14 coefficients (E. Mason pers. comm.).

We have examined various graphs of spiral grain patterns and predictions from the model, comparing predictions to actual.

We have compared the model predictions to observations on two other sites (Tikitere and Forsyth Downs) and on the 17 WQI benchmarking sites considered separately.

The Tikitere data (McKinley *et al.* 1997) consisted of 20 trees, consisting of 12 slower grown trees and 8 faster grown trees. Discs were sampled at 1.4m and approximately 5-metre intervals from 0m up to 30m but, to accomodate the 'radius' and radial growth rate variables in the WQI model, the validation was limited to discs with densitometry at heights 0,5,10, and 15 metres. Spiral grain measurements were available for every second ring.

Note: Spiral grain, but not densitometry, measurements are available on a further 74 trees from another Tikitere study (McKinley *et al.* 2001).

The Forsyth Downs data (Cown *et al.* 2006) consisted of 40 trees, comprising 10 trees from each of 4 stocking rates: 200, 350, 500, and 1000 spha. Spiral grain was measured on rings 2, 4, 6, 8, 10, 15, and 20. To accomodate the 'radius' and radial growth rate variables in the WQI model, the validation was limited to discs at heights 0, 1.4, 5, and 20m.

We have re-fitted the WQI model separately to each of the 17 WQI sites, and also fitted mixed models allowing for different effects of intercept (constant term), radius (average distance from the pith of rings in a 5-ring block) and growth rate (average ring width of a 5-ring block) at site and tree levels.

For simplicity, and to conform with WQI requests not to use their data to develop a new model at this stage, we have used similar models and methods. Scion does not recommend the models shown here for predicting spiral grain.

[1] The signs were adjusted because the opposite convention was used in the data collection phase of the study.

RESULTS

WQI benchmark study results:

R^2 statistics (R^2) were calculated for each site separately based on the errors of predictions from the overall WQI model (Table 3). Cross-validated versions (R^2_{cv}) were calculated based on the errors of predictions from the WQI model fitted to sites other than the one being tested.

An R^2 value of 46.6% (similar to but slightly higher than the value in the WQI report) was obtained when we refitted the WQI model to the full WQI data, although coefficients were somewhat different (Tables 5, 6). We did not attempt to filter data as was done in the original analysis (E. Mason SAS file).

For separate model fits, R^2 statistics ranged from 10% to 60%.

Cross-validated R^2 statistics were slightly lower.

Plots of means over trees for each ring within each disc by site show significant variability in pith-to-bark trends and deviations from the WQI model (Figure 1). These were confirmed by separate analysis of WQI sites, and also a mixed model analysis (Appendix, Tables 7, 8).

Coefficients for models fitted to individual sites varied substantially, and appeared to be significantly different from the overall model. (But see notes on problems with the methodology above.)

Comparisons of mixed model fits showed there was evidence for random effects of radius and radial growth rate at both the site and tree levels (Table 7).

The standard deviations of random effects for *radius* were approximately 0.01 at both the site and tree levels (Table 8). This can be compared to the fixed effect coefficient of -0.0170; the random effect standard deviation is approximately 60% of the estimated effect at both the tree and site levels. This means that at some sites the effect of radius would be expected to even be of opposite sign, (as actually happens for the separate model fits).

The standard deviations of random effects for *radial growth rate* were approximately 0.1 at both the site and tree levels (Table 8). This can be compared to the fixed effect coefficient of 0.18. As was the case for radius, the random effect standard deviation for radial growth rate is approximately 60% of the estimated effect at both the tree and site levels. This means that at some sites the effect of radius would be expected to even be of opposite sign, (as actually happens for the separate model fits).

Random effects of disc height and disc level random effects of radius and radial growth rate were not, but in principle could be, examined.

Tikitere results:

Predictions from WQI (Table 13) model: bias= -1.8, R^2 = 23%, r.s.e. = 4.04 .

Predictions from WQI (Table 14) model: bias = -3.04, R^2 = 20%, r.s.e. = 4.12 .

Note: R^2 values correspond to bias adjusted errors. Otherwise prediction standard errors would be greater than raw data standard errors.

When the WQI model was refitted to the Tikitere data, an R^2 of 46.6%, and substantially different coefficients, were obtained (Table 4).

Plots of means over trees for each ring within each disc by site show deviations from the WQI model (Figure 2, Table 5). The WQI model predicts a steeper decline in spiral grain for the first disc (height 0) and under-predicts spiral grain for the higher discs. The WQI model does not predict the initial rise and then fall of spiral grain in the discs at heights 5, 10, and 15.

Interestingly, the WQI model does predict the small peak in spiral grain at ring 10 in the first disc. This may be a response to thinning.

Forsyth Downs results:

Predictions from WQI (Res 35: Table 13) model: bias= -3.3, R^2 = 25%, r.s.e. = 3.41

Predictions from WQI (Res35: Table 14) model: bias = -3.5, R^2 = 26%, r.s.e. = 3.39

Note: R^2 and r.s.e. values correspond to bias-adjusted errors. Otherwise prediction standard errors would be greater than raw data standard errors.

Plots of means over trees for each ring within each disc by site show deviations from the WQI model (Figure 3, Table 6). The WQI model generally under-predicts spiral grain at Forsyth Downs. WQI model predictions are approximately correct at ring 0 but the model predicts a steeper decline in spiral grain with ring number than observed, under-predicting spiral grain across most ring numbers and heights. The WQI model does not predict the increase in spiral grain for early rings.

CONCLUSIONS and RECOMMENDATIONS

Use of the WQI model:

Linear models, as in the report, do not and cannot adequately explain the patterns of pith-to-bark variation in spiral grain (or other wood properties). This is because the pattern of variation in spiral grain is non-linear. Although there is a non-linear relationship between ring number and radius or growth rate, this is generally monotonic and does not conform to the pattern for spiral grain.

Spiral grain first increases then decreases with distance from the pith, and generally increases with height in the stem, and with growth rate. However caution is needed if applying these relationships for predictive purposes because the effects may not be causal and vary between sites— a single linear model does not explain the variation between sites and trees (genotypes). We have shown here (and elsewhere) that there is substantial variation between sites and trees which cannot be ignored.

Site differences: Clear differences between sites are apparent from Figures 1–3. Site differences are not merely an overall average increase, but the pattern of spiral grain variation from pith to bark varies between sites. On some sites spiral grain decreases significantly more rapidly than predicted and on other (predominantly higher-numbered, more southern sites) decreases less rapidly, suggesting that spiral grain is worse than predicted on southern sites.

Not only are there differences between sites (random site effects), there are differences in the trends in spiral grain and other variables (e.g., greater or lesser effects or radius and ring width).

Use of models for any given purpose:

It is important to note that the efficacy of any model depends on how it would be used. For example the use might be for describing the average trend over WQI sites, and showing that spiral grain generally decreases with distance from the pith, and increases with growth rate, but not for predictive purposes.

However caution is needed. For example at Tikitere or Forsyth Downs there was no obvious effect of tree diameter or stocking. It is therefore possible that the growth rate effect is not causal but only an association due to within-tree correlations. If that is the case, then increasing growth rate by use of different silviculture or seedlots would not necessarily result in an increase in spiral grain. We were advised that the model is seen as ‘more descriptive than predictive’ (E Mason, pers. comm.).

It would therefore be dangerous for FFR to use the WQI model without further testing and better understanding of site- and tree- level variability.

Model selection methodology:

Due to space limitations it is not possible to show all possible models tried, nevertheless the class of models should be defined, and the model selection criterion given. The model selection criterion should not be *ad hoc*, and should be applied in a modelling framework (e.g., mixed models or Bayesian hierarchical models) where the assumptions hold. Ideally it should be based on established criteria such as BIC or AIC criteria, or where there is doubt about asymptotics, posterior probabilities for models.

If multiple models are consistent with the data but no single model is strongly preferred, use of multiple models should be considered. Use of multiple models for predictions will be more robust, and no more difficult for end users if included in a computer program.

Scion mixed model smoothing spline wood quality modelling methodology:

Scion has developed statistical methods and software for mixed smoothing spline methodology more than 5 years ago (Ball 2003, 2004), and non-linear models prior to that (e.g., Tian, Cown and Lausberg 1995). The non-linear models describe the overall trends. The mixed model smoothing spline work is aimed precisely at elucidating the variability in wood properties both within and between stems, which is not possible with the linear model used in the WQI report. The methodology is general and can apply to various types of data such as clonal data or multi-site data, as in the WQI benchmarking study.

Modelling framework: Scion is well aware of the existence of correlation structure in wood property data. We have been developing modelling methodology to allow for this structure and reduce assumptions giving better understanding of the variability. Future models should be developed in a mixed- or Bayesian hierarchical model framework.

Recommendations for future FFR and fundamental research:

FFR should not rely on WQI models for spiral grain or other wood properties. FFR is better to use WQI data where relevant, but ignore WQI models rather than waste time validating them.

The root causes of spiral grain are not well understood. More fundamental and applied research is needed to understand the development of spiral grain. Experiments need to be designed or data selected to:

- understand causes of site variability and/or develop site index system for spiral grain (do we need individual models for individual sites/regions or site types?).
- identify the effects of silviculture (cf apparent peak at point of thinning in Tikitere?)
- estimate effects of genetics (e.g. seedlots and clones)
- attempt to combine the 3, especially site and genetics

Future modelling approaches should incorporate one or more of the following:

- bio-mechanical modelling to understand the implications for tree survival with given tree geometry, wood density, MFA and wind etc,
- mixed smoothing spline or Bayesian hierarchical models, used to study co-variation of spiral grain with other major wood properties and tree geometry

Ring-based models are a natural starting point for such models—a natural way to model wood properties is in terms of ring number (from the pith and/or bark) and height; effects such as radial growth rate and distance from the pith should be evaluated in the context of departures from such ring-based models, i.e., comparing differences in predictions for a given ring number from the pith at a given height.

The structure of variability is complex when modelling multiple within- stem properties, and also allowing for site and genetic factors. Model development is challenging due to the number and structure of different random effects. Modelling methods and models should be developed to:

- use Scion mixed smoothing spline or Bayesian hierarchical models to predict and study the variation of individual wood properties in 2- or 3- dimensions within stems, and how these patterns vary with site, silviculture and genotype;
- build on the Scion mixed smoothing spline or Bayesian hierarchical models to study co-variation of spiral grain with other major wood properties and tree geometry;
- develop combined models incorporating genetic and site variability, with the goal of being able to simulate random trees.

Sampling Strategy:

- The sampling approach used in the WQI studies was a pragmatic approach to validation of the gross within-stem patterns already established in numerous studies, and an attempt to document environmental effects. By its nature, it failed to define the intricate changes in the corewood (where the most rapid changes take place). This achieved its goals, but did not generate a database suitable for use in modelling, because the data were collected in 5-ring sections only, and do not cover the zone of highest grain angles and change in enough detail. The more traditional approach of assessing rings 2, 4, 6, 8, 10, 15, 20, 25, etc, is more appropriate for describing within-stem variation. The 10 trees sampled per site, while generating a noisy dataset, seems sufficient to document differences between sites. Recent studies have indicated that more intensive sampling would merely add to the work load without revealing much more useful information.

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Table 1: Coefficients for WQI model including density (WQI Res35: table 13).

```
> table13.coeffs
           variable  estimate       se
1         intercept  4.391500 0.400700
2 radial.growth.rate -0.228800 0.011040
3           density  0.010960 0.000823
4            radius  0.013280 0.000697
5       disc.height -0.253800 0.018920
6      disc.height2  0.006317 0.000700
```

Note 1. Signs of model predictions should be reversed (i.e. multiply by -1) to conform to the standard that a left hand spiral (grain sloping to the left when looking up the tree) is positive.

Table 2: Coefficients for WQI model (Res35: table 14).

```
> table14.coeffs
           variable  estimate
1         intercept -1.799100
2 radial.growth.rate -0.283900
3      mean.min.temp  0.289400
4            radius  0.014550
5       disc.height -0.289400
6      disc.height^2  0.006938
```

Note 1. Signs of model predictions should be reversed (i.e. multiply by -1) to conform to the standard that a left hand spiral (grain sloping to the left when looking up the tree) is positive.
Note 2. Coefficients are a a revised version of WQI Res35: table 14, supplied by Euan Mason, as per the model fitted by Euan Mason.

Table 3: R^2 and model fit statistics for WQI Sites

```
> wqi.em.df[isite,c("SITEID","SITE")]
```

SITEID	SITE	r2s	r2s.cv	rses.fit	rses.cv	(Intercept)	TMINNIWA	RADIUS	radial.growth.rate	DISKHT	I(DISKHT^2)
1	AK772	24.81	24.20	3.441	3.535	-6.7553	0.83488	-0.0327036	0.01510	0.04650	0.002500
2	AK774	41.61	41.18	2.357	2.408	1.1169	0.08128	-0.0246442	0.13159	0.14733	0.028999
3	RO1664/4	46.61	46.56	2.324	2.380	-2.8538	0.37631	-0.0199586	0.17208	-0.71306	0.192830
4	RO1664	61.45	61.18	1.694	1.726	0.2959	0.09869	-0.0179201	0.18867	0.59455	-0.021622
5	RO2103/2	39.03	37.64	2.804	3.000	3.7379	-1.09705	-0.0049711	0.50352	0.31593	-0.010085
6	WN377	35.75	34.50	1.906	2.024	-7.5411	0.99733	-0.0149520	0.13594	0.04756	0.018535
7	WN306	54.20	54.06	2.389	2.432	-11.6249	1.39171	-0.0221293	0.21800	0.56938	-0.021434
8	WN306/1	41.46	41.34	1.965	1.968	-1.0148	0.17640	-0.0107373	0.19801	0.42321	-0.013397
9	NN405/2	43.67	42.88	2.558	2.688	-0.5112	-0.04246	-0.0259866	0.29287	0.19008	-0.004040
10	NN530/2	41.65	40.55	2.363	2.613	12.6323	-1.31521	-0.0390771	0.01555	0.16196	-0.003899
11	NN405/3	54.20	53.92	1.960	2.026	-5.6365	0.92891	-0.0177708	0.28832	0.62908	-0.024025
12	CY421/2	14.18	10.75	2.192	2.476	5.8278	-1.27653	0.0035242	0.21155	0.57727	-0.018727
13	CY421/8	18.46	17.12	1.734	1.895	10.9130	-1.24054	-0.0200863	-0.10640	0.18391	-0.004350
14	CY421/1	21.12	19.45	1.915	2.111	-4.0004	0.78747	-0.0006272	0.16715	0.53587	-0.018898
15	SD564/1	34.62	34.05	2.580	2.708	-2.9948	0.80276	-0.0080716	0.15225	0.80919	-0.028256
16	SD564/3	39.99	37.57	1.841	2.378	-4.1121	-0.38641	0.0094398	0.50885	1.06695	-0.037814
17	SD564/4	52.97	52.68	1.630	1.883	1.7488	-0.65567	-0.0133871	0.28034	2.07455	-0.249895

Table 4: WQI model refitted to Tikitere 5-ring block data.

```
> summary(sg.wqi.new.fit1)

Call:
lm(formula = sg ~ radial.growth.rate + radius + disc.height +
    I(disc.height^2), data = tksg.df3)

Residuals:
    Min      1Q  Median      3Q     Max
-10.115  -2.077  -0.199   1.946   8.466

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)        -1.25834    1.01467   -1.24  0.21626
radial.growth.rate  0.18340    0.04402    4.17  4.5e-05
radius             -0.00153    0.00344   -0.44  0.65713
disc.height         0.85786    0.12448    6.89  5.9e-11
I(disc.height^2)   -0.03079    0.00852   -3.62  0.00037

Residual standard error: 3.06 on 217 degrees of freedom
Multiple R-Squared: 0.466,Adjusted R-squared: 0.456
F-statistic: 47.3 on 4 and 217 DF,  p-value: <2e-16
```

Table 5: Spiral grain observed and predicted tree means for Tikitere by ring and disc height class, as shown in Figure 2. Columns are: `ring` = ring number from pith, `disc.ht` = disc height (metres from ground); `sg` = observed mean of spiral grain, `sg.sem`=standard error of spiral grain, `WQI-13`, `WQI-14` = predictions from WQI models (WQI Res 35: Tables 13, 14 resp., signs adjusted).

```
> tkmeans.tbl
   ring disc.ht    sg sg.sem WQI-13 WQI-14
1     2       0  2.86   0.79  5.574  4.384
2     4       0  2.24   0.61  4.041  2.875
3     6       0  1.15   0.69  1.940  0.621
4     8       0  0.49   0.69  1.443  0.150
5    10       0  1.44   0.49  2.104  0.909
6    12       0  0.28   0.60  1.021 -0.194
7    14       0  0.41   0.63 -0.722 -2.184
8    16       0 -0.12   0.74 -1.399 -3.001
9    18       0 -0.59   0.80 -1.843 -3.429
10   20       0 -0.50   0.82 -1.916 -3.409
11    2       5  6.41   0.67  6.457  5.105
12    4       5  7.43   0.75  5.285  4.096
13    6       5  7.94   0.77  4.226  2.995
14    8       5  6.90   0.87  3.128  1.762
15   10       5  5.86   1.18  1.992  0.677
16   12       5  4.46   1.12  1.128 -0.291
17   14       5  3.51   1.02  0.367 -1.040
18   16       5  1.79   0.83  0.058 -1.434
19   18       5  2.34   0.96 -0.113 -1.682
20    2      10  6.28   0.50  6.767  5.527
21    4      10  7.88   0.64  6.001  5.121
22    6      10  8.66   0.57  5.034  4.051
23    8      10  7.76   0.61  4.004  2.913
24   10      10  6.93   0.75  2.748  1.547
25   12      10  5.38   0.85  1.993  0.785
26   14      10  5.46   1.20  1.215 -0.065
27    2      15  5.93   0.45  5.934  4.632
28    4      15  7.27   0.47  5.623  4.568
29    6      15  7.55   0.82  4.699  3.659
30    8      15  6.75   0.99  3.840  2.782
31   10      15  6.00   1.93  3.178  2.070
32    2     20+  5.72   0.52  5.283  3.879
33    4     20+  9.31   1.61  4.850  3.536
```

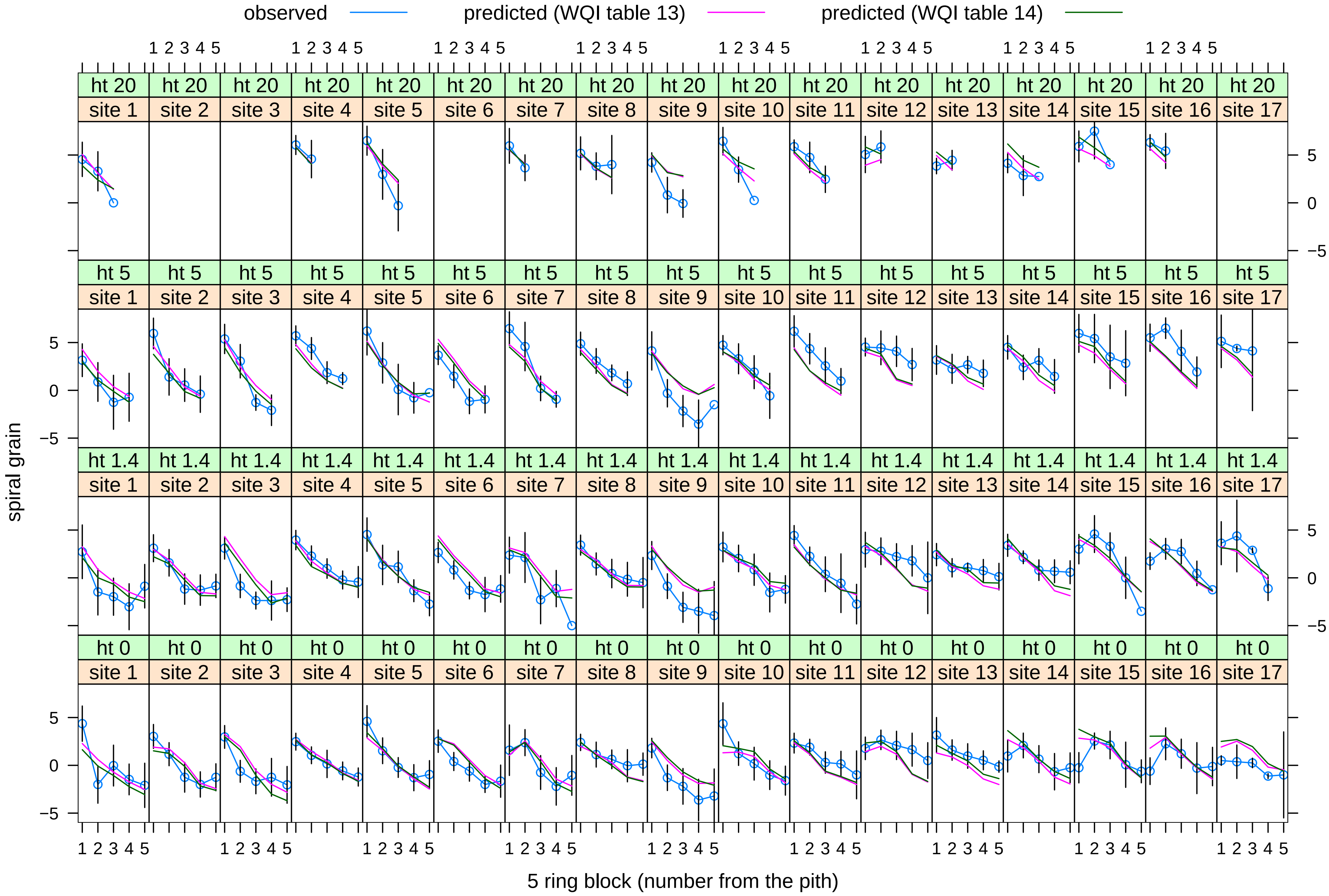
Table 6: Spiral grain observed and predicted tree means for Forsyth Downs by ring and disc height class, as shown in Figure 3. Columns are: `stocking` = stocking (number of stems per hectare); `ring` = ring number from pith; `disc.ht` = disc height (metres from ground); `sg` = observed mean of spiral grain; `sg.sem` = standard error of mean of spiral grain; `WQI-13, WQI-14` = predictions from WQI models (WQI Res 35: Tables 13, 14 resp, signs adjusted.).

```
> fdmeans.tbl
   stocking ring disc.ht    sg sg.sem WQI-13  WQI-14
 1      200    2       0  5.39   0.62  3.600  3.4560
 2      200    4       0  4.41   0.58  2.822  2.9539
 3      200    6       0  6.95   0.74  2.948  3.1597
 4      200    8       0  5.25   1.04  0.775  0.4605
 5      200   10       0  3.58   1.28 -0.582 -1.0796
 6      200   15       0 -0.17   1.02 -2.741 -3.1809
 7      200   20       0  0.35   1.00 -3.635 -4.0239
 8      200    2       1  5.67   0.51  3.822  3.3736
 9      200    4       1  5.55   0.85  3.544  3.7527
10      200    6       1  5.65   0.97  2.032  1.6678
11      200    8       1  3.85   1.01  0.732  0.1660
12      200   10       1  2.48   1.02  0.208 -0.5981
13      200   15       1 -1.32   1.26 -2.526 -3.0868
14      200   20       1 -0.85   1.34 -3.061 -3.4011
15      200    2       5  6.25   0.92  4.882  4.6499
16      200    4       5  7.40   0.85  3.724  3.6091
17      200    6       5  7.70   0.99  2.364  1.9355
18      200    8       5  5.58   1.29  1.189  0.5449
19      200   10       5  4.30   0.85  0.376 -0.3406
20      200   15       5 -1.60   1.30 -1.818 -2.0990
21      200   20       5 -7.08   3.29 -1.484 -3.1398
22      200    2      20  6.08   0.69  5.202  4.7090
23      200    4      20  5.89   0.87  4.115  3.8802
24      200    6      20  5.97   1.19  3.320  3.1841
25      200    8      20  6.31   0.96  2.584  2.6002
26      200   10      20  5.42   1.29  2.089  1.7643
27      350    2       0  4.28   0.77  3.016  3.2584
28      350    4       0  5.33   0.58  2.693  3.1136
29      350    6       0  6.17   0.78  1.387  1.3883
30      350    8       0  4.62   0.99 -0.656 -0.8655
31      350   10       0  4.03   0.77 -1.599 -1.8385
32      350   15       0  1.90   0.81 -3.557 -3.5375
33      350   20       0  0.53   0.90 -4.091 -3.7451
34      350    2       1  4.55   0.39  3.753  4.0010
35      350    4       1  6.03   0.87  3.187  3.6178
36      350    6       1  6.05   1.12  1.247  1.0621
```

	stocking	ring	disc.ht	sg	sg.sem	WQI-13	WQI-14
37	350	8	1	4.80	1.03	-0.679	-1.0441
38	350	10	1	3.12	1.18	-1.135	-1.6240
39	350	15	1	1.85	0.99	-3.022	-3.0466
40	350	20	1	0.33	1.24	-3.416	-3.3888
41	350	2	5	6.20	0.82	4.637	4.5890
42	350	4	5	8.12	1.14	2.889	2.7449
43	350	6	5	8.00	1.33	1.482	1.2011
44	350	8	5	6.85	1.32	0.555	0.2286
45	350	10	5	4.33	1.36	-0.555	-0.6770
46	350	15	5	1.73	1.36	-1.826	-1.7234
47	350	20	5	-0.19	1.60	-0.661	-2.5800
48	350	2	20	5.68	0.57	4.805	4.4931
49	350	4	20	7.57	1.18	3.800	3.5380
50	350	6	20	8.89	0.83	3.005	2.8789
51	350	8	20	8.79	1.10	2.041	2.0722
52	350	10	20	8.14	1.79	1.443	1.4497
53	500	2	0	4.05	0.97	3.352	3.4332
54	500	4	0	3.50	0.79	2.694	2.8403
55	500	6	0	4.24	0.76	0.527	0.3565
56	500	8	0	3.90	0.69	-0.371	-0.6781
57	500	10	0	1.52	1.27	-1.399	-1.7935
58	500	15	0	-1.23	1.28	-3.035	-2.9457
59	500	20	0	-1.00	1.03	-3.584	-3.4405
60	500	2	1	4.83	0.57	3.486	3.2487
61	500	4	1	5.90	0.58	2.238	2.2975
62	500	6	1	4.30	0.83	0.847	0.3758
63	500	8	1	3.38	0.71	-0.326	-0.7532
64	500	10	1	2.08	0.88	-0.991	-1.4417
65	500	15	1	-0.20	0.99	-2.814	-2.6134
66	500	20	1	-0.57	0.47	-3.017	-3.0871
67	500	2	5	5.12	1.11	4.225	3.9247
68	500	4	5	7.28	0.42	2.890	2.6108
69	500	6	5	7.36	0.47	1.241	0.9447
70	500	8	5	6.58	0.86	0.350	-0.0067
71	500	10	5	3.40	0.84	-0.108	-0.3548
72	500	15	5	-0.85	1.39	-1.753	-1.5684

	stocking	ring	disc.ht	sg	sg.sem	WQI-13	WQI-14
73	500	20	5	-0.83	1.45	-1.799	-2.9044
74	500	2	20	6.14	0.74	4.904	4.3513
75	500	4	20	8.53	0.65	3.995	3.6069
76	500	6	20	8.17	0.98	3.128	2.8227
77	500	8	20	7.47	0.96	2.329	2.2985
78	500	10	20	6.89	1.19	1.535	1.3180
79	1000	2	0	4.05	1.02	3.319	3.5332
80	1000	4	0	4.42	0.85	1.643	1.7187
81	1000	6	0	3.83	0.86	-0.249	-0.5827
82	1000	8	0	2.00	0.99	-1.062	-1.4280
83	1000	10	0	1.10	1.07	-1.879	-2.0935
84	1000	15	0	0.12	0.73	-3.492	-3.1120
85	1000	20	0	-1.07	0.79	-3.717	-3.2803
86	1000	2	1	5.05	0.60	3.587	3.5468
87	1000	4	1	5.67	0.60	1.310	1.1210
88	1000	6	1	4.75	0.83	-0.384	-0.4796
89	1000	8	1	2.08	1.24	-1.189	-1.3093
90	1000	10	1	1.67	1.04	-1.971	-1.9351
91	1000	15	1	0.49	0.68	-3.312	-2.5274
92	1000	20	1	-1.70	1.13	-2.884	-2.8070
93	1000	2	5	5.88	0.68	4.362	3.8810
94	1000	4	5	7.24	0.79	2.188	1.8919
95	1000	6	5	6.53	0.86	0.602	0.3702
96	1000	8	5	4.65	0.86	-0.056	-0.0915
97	1000	10	5	3.12	0.82	-1.290	-0.7703
98	1000	15	5	-0.12	1.13	-2.295	-1.4203
99	1000	20	5	-0.44	1.25	-1.395	-2.2522
100	1000	2	20	5.67	0.47	4.367	3.9250
101	1000	4	20	6.06	1.06	3.243	2.9787
102	1000	6	20	4.42	1.33	2.370	2.4010
103	1000	8	20	4.19	1.39	1.210	1.6149
104	1000	10	20	3.94	1.23	1.159	1.4152

Fig 1: Observed and predicted values for WQI site means (error bars = 2*SEM)



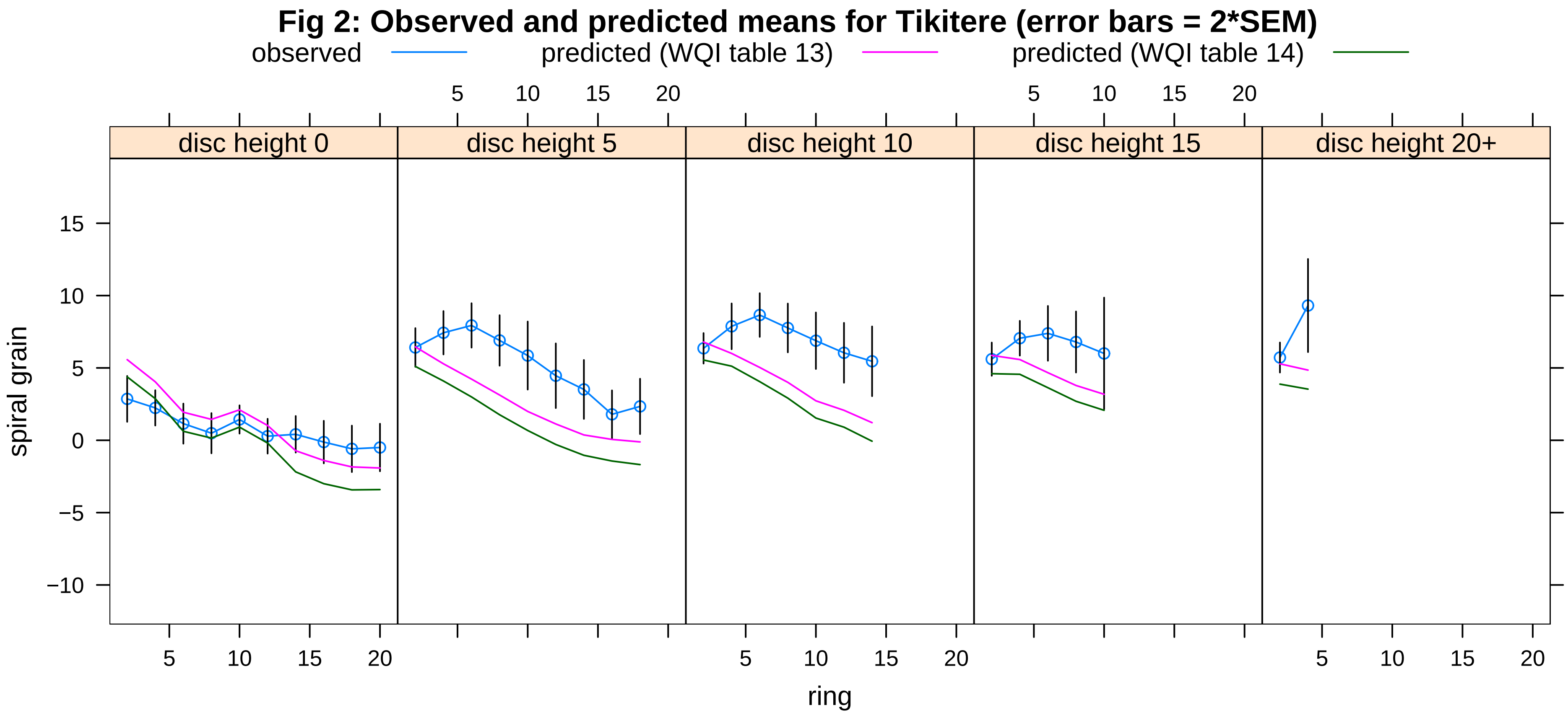
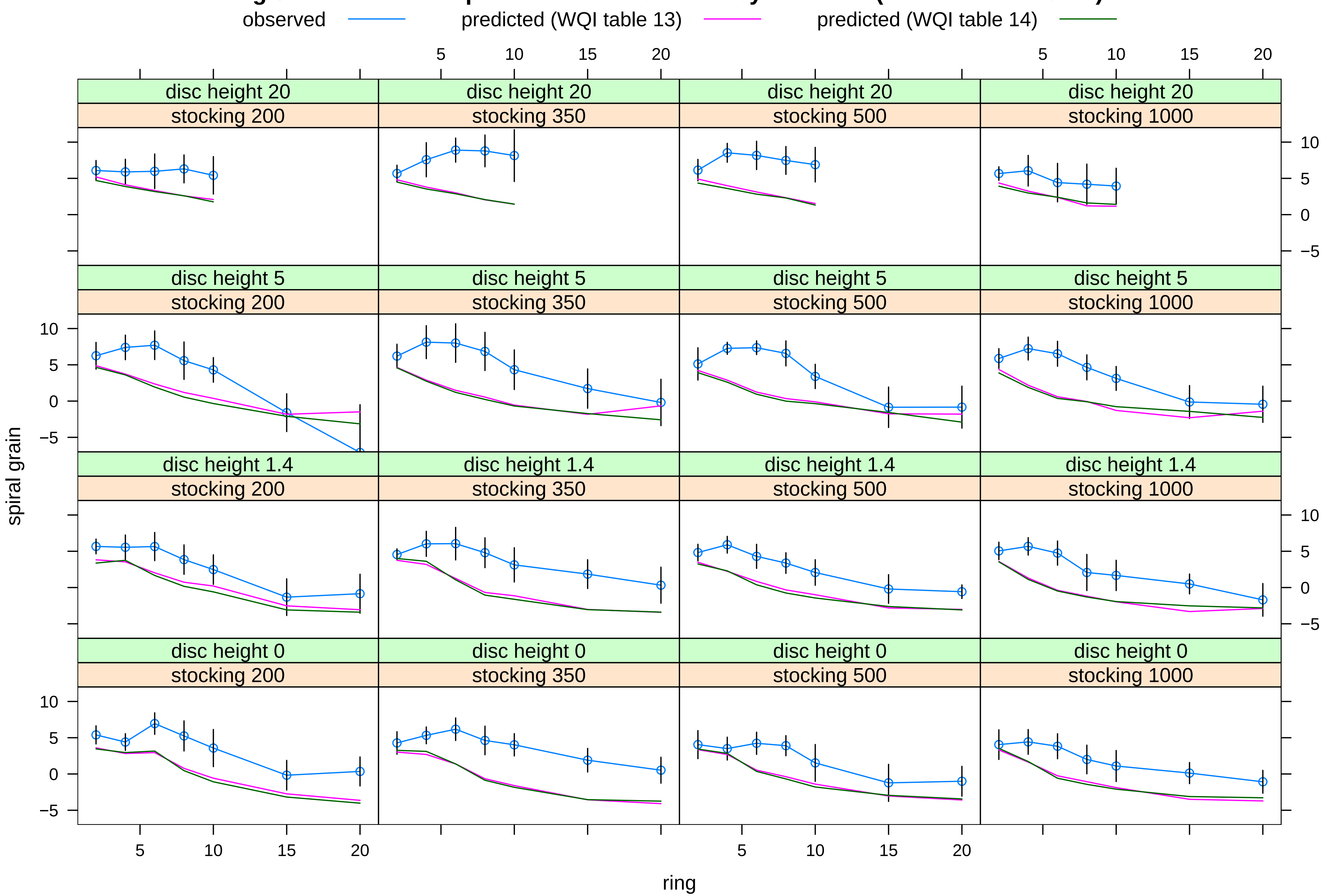


Fig 2: Observed and predicted means for Tikitere (error bars = 2*SEM)
observed
predicted (WQI table 13)
predicted (WQI table 14)
disc height 0
disc height 5
disc height 10
disc height 15
disc height 20+
spiral grain
ring

Fig 3: Observed and predicted means for Forsyth Downs (error bars = 2*SEM)



APPENDIX 1: Mixed model version of the WQI model.

Table 7: Model comparison for mixed model fit to 17 WQI sites.

```
> anova(wqi.sg13.lme0,wqi.sg13.lme,wqi.sg13.lme1)
   Model df   AIC   BIC logLik   Test L.Ratio p-value
       1 10 18015 18079  -8998
       2 15 17611 17706  -8790 1 vs 2   414.4  <.0001
       3 17 17086 17194  -8526 2 vs 3   528.4  <.0001
```

Note:

Model 1: includes only constant random effects at the site, tree, and disc levels; Model 2 includes random effects for radius and radial growth rate at the site level; and Model 3 includes random effects for radius and radial growth rate at the site and tree levels. Model 3 is preferred by the AIC and BIC criteria (smaller values are better), and also large increase in log likelihood, meaning it is likely to give better predictions and is more likely to be the true model.

Table 8: Model summary for mixed model fit to 17 WQI sites.

```
> summary(wqi.sg13.lme1)
Linear mixed-effects model fit by REML
 Data: wqi.em.df[s13, ]
    AIC   BIC logLik
  17086 17194  -8526

Random effects:
 Formula: ~RADIUS + radial.growth.rate | site
 Structure: General positive-definite, Log-Cholesky parametrization
                   StdDev   Corr
(Intercept)        1.490134 (Intr) RADIUS
RADIUS             0.009976 -0.566
radial.growth.rate 0.108664 -0.941  0.540

 Formula: ~RADIUS + radial.growth.rate | TREEID %in% site
 Structure: Diagonal
        (Intercept)  RADIUS radial.growth.rate
StdDev:      0.9918 0.01046             0.1027

 Formula: ~1 | DISKHT %in% TREEID %in% site
        (Intercept) Residual
StdDev:       1.131    1.495

Fixed effects: sg ~ TMINNIWA + RADIUS + radial.growth.rate + DISKHT + I(DISKHT^2)
                     Value Std.Error   DF t-value p-value
(Intercept)        -0.1798    0.6229 3669  -0.289  0.7729
TMINNIWA            0.1397    0.0643 3669   2.174  0.0297
RADIUS             -0.0170    0.0027 3669  -6.280  0.0000
radial.growth.rate  0.1826    0.0304 3669   6.003  0.0000
DISKHT              0.4146    0.0371  412  11.162  0.0000
I(DISKHT^2)        -0.0137    0.0018  412  -7.787  0.0000
 Correlation:
                   (Intr) TMINNI RADIUS rdl.g. DISKHT
TMINNIWA           -0.726
RADIUS             -0.377 -0.002
radial.growth.rate -0.582 -0.020  0.513
DISKHT             -0.118 -0.010  0.027  0.031
I(DISKHT^2)         0.082  0.019 -0.008 -0.010 -0.975

Standardized Within-Group Residuals:
    Min      Q1     Med      Q3     Max
-5.2774 -0.5597  0.0134  0.5594  4.2486

Number of Observations: 4236
Number of Groups:
              site             TREEID %in% site DISKHT %in% TREEID %in% site
                17                          150                          564
```