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Improved models of the effects of winter chilling on blackcurrant (*Ribes nigrum L.*) show cultivar specific sensitivity to warm winters

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A Abstract

Sufficient chilling in winter is essential for many perennial crops to start growing in spring and to produce good yields. Using blackcurrants as an example we have developed improved models which can help identify varieties resilient to the variable winters expected as the climate warms. Controlled temperature experiments were used to calibrate 3 proposed models of chilling accumulation requirements for a number of commercial blackcurrant cultivars. The first model assumed a linear relationship between bud break and chilling accumulation, the second a quadratic relationship which allows for the possibility of over-chilling and the third, an asymmetric quadratic relationship in which the maximum achievable effectiveness is temperature dependent. The models were then applied to data on selected cultivars gathered from blackcurrant growers across the United Kingdom and the third model was found to provide the best fit for the data, suggesting that long warm winters do not have the same effect as short cold winters in terms of the satisfaction of chilling requirement. Further, the degree to which temperature affects maximum bud break varies by cultivar. We discuss the potential effects of differing timing of chill on the applicability of the models presented.

Key Words: *Ribes*, winter chilling, bud break, Dormancy, chill models, climate change

B Introduction

Adequate winter chilling is required for the satisfaction of the chilling requirement that is needed for optimal bud break and flowering of many temperate fruit crops including blackcurrant (*Ribes nigrum* L.). The potential reduction of winter chill with climate change is of particular concern to growers of many woody fruit crops in the UK (Atkinson *et al*., 2004, 2013) and elsewhere (Snelling and Langford, 2002; Oukabli et al., 2003; Andersen et al., 2017) as it can cause erratic bud burst and increase the spread of flowering, thus leading to reduced crop yields and quality. Quantification of the amount of winter chilling has been the subject of much research on a range of crops with widely differing requirements both for cold during the dormant period and for warming to facilitate the actual bud break once chilling has been satisfied. Since the early work of Weinberger (1950) a wide range of chilling functions have been proposed to quantify the chill experienced by different crops (reviewed by Dennis, 2003; Atkinson et al., 2013; Sunley et al., 2006). The most widely used chilling models either weight all temperatures below 7.2°C or all temperatures between 0°C and 7.2°C equally, though it has been recognised that different temperatures can have a different effect on chilling satisfaction leading to the development of more specialised chilling units for specific species including the 'Utah' units that have been derived for peach (Richardson et al., 1974).

For blackcurrant, there is good evidence that the impact of chilling increases approximately exponentially as temperature decreases (Bidabe, 1967; Lantin, 1973; 1977; Jones et al., 2013). Nevertheless, various studies have shown that the chilling requirement differs substantially between cultivars adapted for different climates (Atwood, 2003; Jones et al., 2013; Lantin, 1977). Furthermore, Jones et al. (2013) found evidence that excessive chilling could even inhibit the chilling response in some cultivars and proposed a model in which bud break can be modelled as a quadratic response to temperature related chilling accumulation. This allows for supra- as well as the more usual sub-optimal chilling, but the effects are symmetrical and the maximum achievable bud break is independent of temperature. The implication would be that 100% bud break would be achievable if fairly warm temperatures were applied for long enough. It therefore makes sense also to consider the possibility of generalizing the Jones models to one that allows an asymmetric response and where maximum achieveable bud break depends on the temperature history.

Previous model fits have used either regression or non-linear fits assuming normal residuals (Jones et al., 2013). This is a reasonable approximation when moderate levels of bud break are achieved. However, field experiments can lead to very high or very low levels of bud break and here we refine the fitting methods to take account of the binomial distribution in the data, which is particularly important when there has been either very high or very low bud break.

We used controlled temperature data to calibrate three models (Lantin, Jones and generalized Jones) for various cultivars, assessing the degree to which the response to temperature is cultivar specific. We then validated the models against field data from around the country.

We found that the parameters were cultivar specific and the generalized Jones model had a better fit suggesting that cultivars have an optimal chilling range; that a long warm winter will have a different impact on bud break than a short cold one; and that these effects are cultivar specific. Thus it is both possible to characterise the chilling requirements of a cultivar and important to select cultivars suitable for the conditions in which they will be cultivated. Expressing climates of the different regions where blackcurrants are cultivated in terms of chilling hours below 7.2°C, these can vary from less than 1000 h in the warmest areas such as some in New Zealand to approaching 5000 h over a winter in more Continental climates. Even at any one site (such as Dundee, Scotland) the value can vary by 25% between years (Jones et al., 2014). The lowest levels of chilling in the UK are to be found in Kent and the West Midlands especially Herefordshire (Atkinson et al., 2004), which are the areas where the most serious budbreak problems have been reported in blackcurrant. Any transition from the endodormancy phase to ecodormancy requires the full chilling requirement to be satisfied, so that the timing of endodormancy is determined by environmental conditions.

C Methods

C.1 Bud break experiments

C.1.1 Experiment 1: model calibration

Controlled temperature experiments for model calibration were performed at the Scottish Crop Research Institute (now the James Hutton Institute) in the winter of 2007/2008 in which different combinations of cultivar, temperature and chilling time were considered. For full details of the experiments see Jones et al. (2013). In short, four equivalent 12-bud cuttings were taken in mid-October 2007 from 4-5 year old bushes in the field of each of 20 cultivars from a wide range of geographical provenances where blackcurrants are cultivated and subsequently transferred at random to controlled environment rooms and kept at a constant temperature (either -5°C, 0°C, 5°C or 10°C) for periods of 35, 63, 91, 119 or 147 days.

After chilling, the cuttings were transferred to a glasshouse maintained at 20°C for 6 weeks, which provided an environment conducive to budbreak, and records of bud burst taken at weekly intervals; recording ceased after 6 weeks as no further budburst was seen after this period. Dead buds were excluded from the analysis and any bud which showed initial signs of bud swelling or further progression was considered to have broken.

C.1.2 Experiment 2: model validation

C.1.2.1 Plant material

Six commercially important UK cultivars were selected from those studied in Experiment 1. Cuttings were sampled in the field every 2 weeks from 07/10/2015 until 22/03/2016 by five growers from three key blackcurrant-growing regions of the UK (1 in Scotland, 2 in Herefordshire and 2 in Kent) and these samples sent to the James Hutton Institute for monitoring of bud burst. Cuttings were maintained at 20°C and after 21 days the top 13 buds were examined. Dead buds were excluded from the analysis and any buds that had broken to leaf or flower were considered to have broken. Each sample consisted of 2 cuttings each from 3 bushes of each cultivar, though not all cultivars were available at all grower sites (see Table A1 in Appendix AA for a table of the number of cuttings by cultivar and grower and Table A2 for the dates on which the cuttings were received by cultivar.).

C.1.2.2 Temperature data

Hourly data from the UK Meteorological Office stations at NIAB-EMR (East Malling), Fittenden and Manston in Kent, Pershore in Herefordshire, Leuchars in Fife, together with data from East Adamson Farm and The James Hutton Institute in Angus, were obtained for 1 October 2015 through to 22 March 2016. For each region (Kent, Herefordshire and Eastern Scotland) the mean average hourly temperature over all stations was taken. Dundee tended to have lower temperatures whilst Herefordshire and Kent had similar average temperatures though Herefordshire was somewhat more variable than Kent (See Figure 1 for the temperatures from 01/12/2015-31/01/2016).

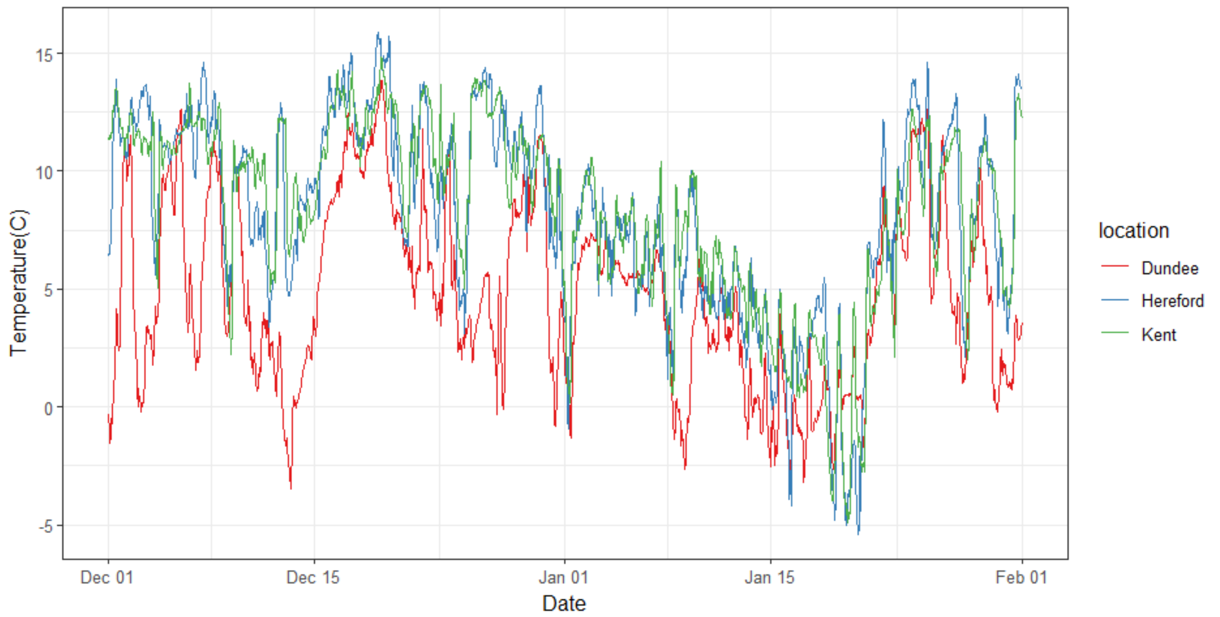

Figure 1 Averaged temperature data (see text for details) from 01/12/2015 until 31/01/2016 for Dundee, Herefordhsire and Kent.

C.2 Model formulation

Effectiveness (E) is defined as the proportion of buds breaking. There are many factors which influence Effectiveness and chilling is an important one so we consider 3 different models of the relationship between temperature and the Effectiveness due to chilling (E_c). The 3 functions described below were fitted to the controlled temperature data from Experiment 1 using day as the unit of time using general non-linear modelling implemented in the gnm package (Turner and Firth 2015) in R (R Core Team 2107). We are using proportions so we work with the logit of effectiveness due to chilling (E_c):

$$logit(E_c) = log\left(\frac{E_c}{1 - E_c}\right).$$

This accounts for the fact that proportions are bounded at zero and 1 and is approximately linear when E takes intermediate values. Logit(E) increases with the proportion of buds broken being zero when E=0.5. Negative values indicate that fewer than half the buds have broken and positive values indicated that more than half the buds have broken.

C.2.1 Lantin model:

The Lantin model assumes that the chilling contribution from any time is a negative exponential of the temperature at that time. The total chilling accumulation then sums the contributions from all times, *t*, so at temperature, *T*, (which may vary with time, t) chilling accumulation *C* is:

$$C = \int_0^t e^{-aT} dt$$

The logit of Effectiveness due to chilling is a linear function of chilling time:

$$logit(E_c) = b_0 + b_1 C$$

C.2.2 Jones model:

The same model is used for chilling accumulation, C and a quadratic term is introduced to allow for supra-optimal chilling so effectiveness E_c is:

$$logit(E_c) = b_0 + b_1 C + b_2 C^2$$

The construction of this function means that the optimum chilling time (the chilling time which will lead to the largest proportion of buds breaking) increases as temperature increases and the maximum achievable effectiveness is independent of temperature. Therefore, whilst increasing the temperature increases the chilling time necessary to attain maximum effectiveness, keeping a cutting plant even at 20°C for long enough would, theoretically, still achieve maximum effectiveness according to this model, which may be unrealistic at extreme temperatures.

C.2.3 Generalized Jones model:

The Jones model is generalized so that the maximum effectiveness due to chilling becomes dependent on temperature T. Consider

$$logit(E_c) = b_0 + b_1 \int_0^t e^{-aT} dt + b_2 \left(\int_0^t e^{-(k+1)aT} dt \right)^2$$

If k=0, this reduces to the Jones model. It is a quadratic function of chilling accumulation where the temperature weighting for the quadratic term is allowed to differ from that of the linear term.

Assuming $b_2<0$ and a>0 then the effect of increasing temperature, T depends on k as follows (table 1.):

Table 1 The effect of k have on the optimum chilling time and maximum achievable effectiveness

	Optimum Chilling Time	Maximum Effectiveness max(E)
k<-0.5	Decreases	Decreases
k=-0.5	Independent	Decreases
-0.5<k<0	Increases	Decreases
k=0	Increases	Independent
k>0	Increases	Increases

C.3 Parameter estimation, model fitting and selection.

The models are highly non-linear, therefore it is not possible to compare model fit using standard methods such as AIC or likelihood ratio tests which compare the numbers of parameters in the model to the deviance explained. Therefore the models are calibrated to controlled environment data and the residuals assessed for bias which would indicate poor formulation of the model. The calibrated models are then applied to independent data as an offset and the quality of the fit compared for the three models. No temperature related parameters are estimated during the second stage which allows the addresses the possibility of over-fitting to the initial, controlled temperature data-set. The models were fitted within a generalised mixed modelling framework to the 2007/2008 controlled temperature data from Experiment 1 to obtain parameters that minimized the residual deviance. The AICs of the different models were considered and residuals assessed for bias. The parameters from these experiments were then applied to the temperature data described in section 3.1.2 to calculate for each proposed chilling model (parameterised as described above using data from Experiment 1), the predicted contribution of chilling accumulation to effectiveness logit(E_c), for each cultivar, location and sampling date in the field data collected in 2015/16 for Experiment 2. The samples used in Experiment 2 were collected from across the United Kingdom and chilling accumulation is one of a number of factors such as soil type and moisture(for which Location is a proxy); and cultivation practices (for which Grower is a proxy) that may influence effectiveness and the influence may vary by cultivar. Therefore, a binomial generalized linear mixed model was fitted to the 2015/16 field data using the predicted logit(Ec) as an offset and including cultivar and location effects together with their interaction; and grower as a random effect as follows,

$$\text{logit(Effectiveness)}=\text{Cultivar}+\text{Location}+\text{Cultivar:Location}+\text{(Grower)}+\text{offset}(\text{logit}(E_c))$$

Where E_C is the predicted contribution from the chilling model (see section 3.2) being tested. This allows us to compare between the models because the fitting of the chilling accumulation models for the offsets was performed on data from Experiment 1 and the structure of the model of overall effectiveness model fitted to data from Experiment 2 does not depend on which model of chilling accumulation is being tested.

The fact that different cultivars are grown in different parts of the country means that the data is very unbalanced and it is not possible to achieve convergence in the mixed model framework. Therefore in order to consider sampling date as a covariate, it is necessary to treat grower as a fixed factor and fit an unbalanced binomial generalized linear model (Faraday 2005).

logit(Effectiveness)=Cultivar+Location+Cultivar:Location+Location:Grower+Sampling_Date+offset(logit (E_c)).

The level of imbalance with respect to cultivar and grower in the second model means that the first (mixed effects) model must be used to assess the significance of Cultivar and Location, but the second model can be used to assess whether the inclusion of sampling date improves the model fit.This is because no cultivar is planted in every location but sampling date is treated as a covariate and each location is measured on every sampling date.

D Results

When fitted to the 2007/2008 data as discussed in section C3 all three models showed significant differences in parameter estimates between cultivars ($p<0.05$) . There is considerable variation in the proportion of buds breaking within each treatment combinatioin which suggests that chilling accumulation is not the only influence on the proportion of buds breaking (see Appendix B.1-B.3). In addition, the nature of binomially distributed data is that greater variation is to be expected where bud- break is expected to be close to 50% than when it is close to 0% or 1%. However, the removal of structure from the residuals would indicate that the model is accounting for the contribution of chilling accumulation to budbreak. The Lantin model shows considerable structure in the residuals which is removed by the Jones and generalized Jones models (see Appendix B.4). The generalized Jones model has *k* significantly different from 0 ($p<0.05$) for 7 of the cultivars suggesting that the maximum effectiveness of these cultivars is particularly sensitive to temperature (Table 22). Table 33 shows the parameters obtained from the controlled temperature experiment, Experiment 1, which will be used to calculate the offset for cultivars submitted by growers in the 2015/2016 field experiment, Experiment 2. Full model details of the fitted values are in Appendix B and pictures in supplementary information.

Table 2 Estimated values of k for the Generalized Jones model. cultivars with a * have a value significantly different from 0 at the 95% confidence level

Cultivar	k	s.e(k)
Ben Starav	-6.06	3.933
Ben Klibreck*	**-2.18**	**0.814**
Ben Avon*	**-1.96**	**0.416**
Ben Gairn*	**-0.69**	**0.108**
Ben Lomond*	**-0.36**	**0.029**
Ben Baldwin*	**-0.35**	**0.031**
9521-2*	**-0.34**	**0.048**
Ben Brodtorp*	**-0.27**	**0.067**
Ben Andega*	**-0.23**	**0.041**
Ben Dorain	-0.09	0.115
Ben Tirran	-0.04	0.098
9137-2	-0.04	0.087
Amos Black	0.22	0.113
Pilot Mamkin	0.22	0.239
Ben Hope	0.32	0.381
B1834	0.35	0.299
Ben Hedda	0.62	0.668
9134-7	0.70	0.482
9559-6	1.21	1.579
Ben Vane	2.26	2.460

For the 2015/2016 data, using the generalized Jones model gave the lowest deviance, had the lowest AIC (table 4) and showed the lowest bias in the residuals (Figure 22). Temperatures over that winter were fairly warm (so plants were not subjected to over-chilling) suggesting that the improvement in fit of the Generalized Jones model relative to the Jones model was related to the temperature dependence of the maximum rather than asymmetric effects of over- and under-chilling.

Table 3 parameters for the Generalized Jones model from the controlled temperature data for cultivars submitted by growers in 2015/2016. There were significant differences in parameter estimates between cultivars ($p<0.05$) for all 4 parameters.

Cultivar	b_1	b_2	a	k (s.e)
Ben Dorain	7.92e-02 (1.320e-02)	-2.29e-04 (7.789e-05)	-1.03e-01 (1.219e-02)	-9.14e-02 (1.146e-01)
Ben Gairn	8.76e-02 (1.296e-02)	-3.72e-04 (7.429e-05)	-5.26e-02 (9.436e-03)	-6.94e-01 (1.075e-01)
Ben Hope	3.35e-02 (6.298e-03)	-4.96e-05 (4.117e-05)	-1.47e-01 (1.811e-02)	3.17e-01 (3.814e-01)

Ben Klibreck	3.90e-02 (8.978e-03)	-2.40e-05 (4.408e-05)	-6.14e-02 (2.176e-02)	-2.18e+00 (8.144e-01)
Ben Starav	3.55e-02 (4.812e-03)	-3.16e-06 (1.347e-05)	-3.25e-02 (1.582e-02)	-6.06e+00 (3.933e+00)
Ben Tirran	7.77e-02 (1.194e-02)	-2.18e-04 (7.041e-05)	-1.29e-01 (1.293e-02)	-3.90e-02 (9.814e-02)

Table 4 Residual deviance and AIC for the 3 models.

Model	Res. Deviance	Res. d.f.	AIC
Lantin	6594.8	1382	6622.8
Jones	6066.3	1382	6094.3
Gen. Jones	5885.7	1382	5913.7

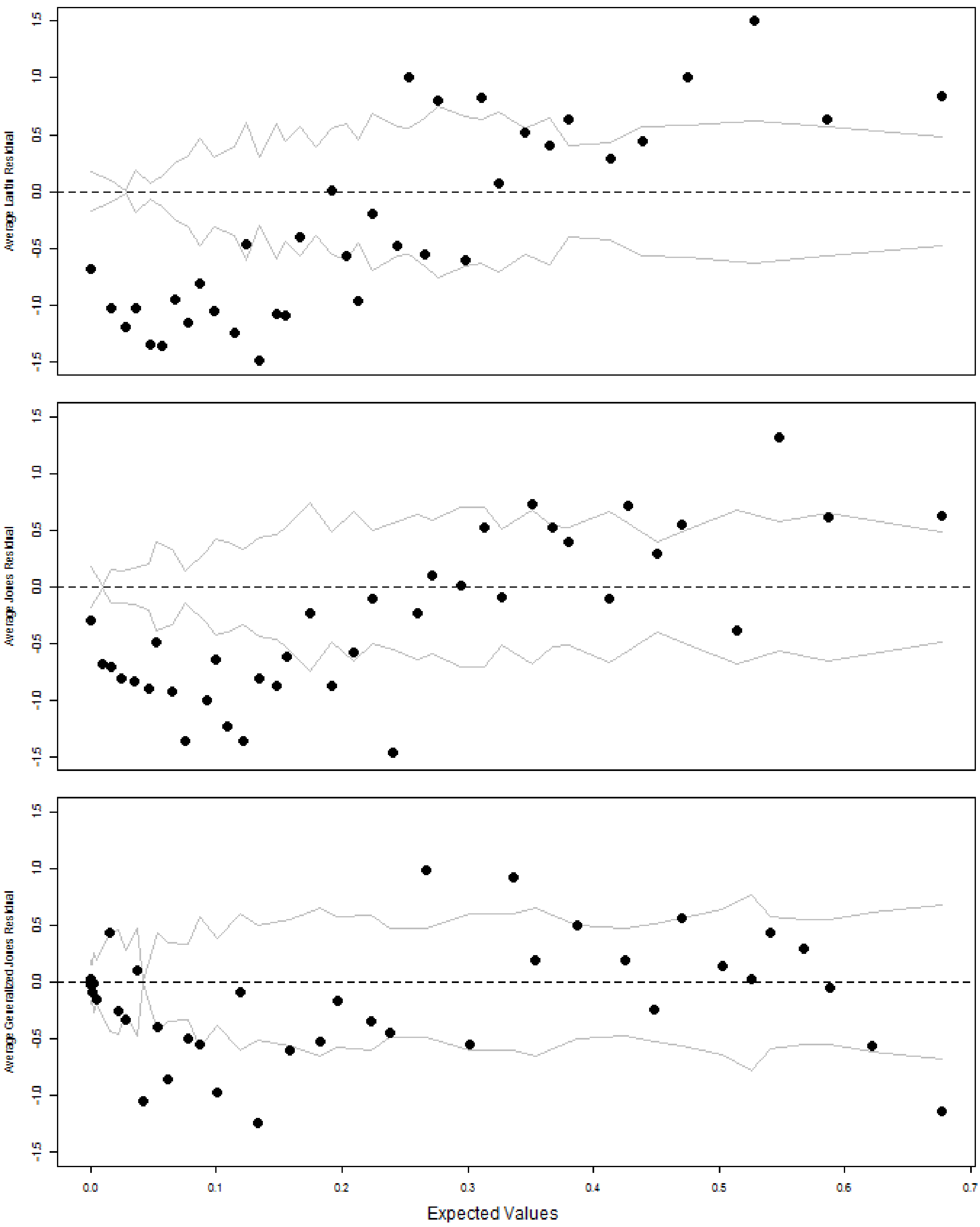

Figure 2. Binned residuals from the three models fitted to data from 03 November 2015 onwards. The points are the average residuals for each fitted value and the grey lines the boundaries in which 95% of values would be expected to lie if the model is appropriate.

Cultivar, Location and the interaction between them (Cultivar:Location) were all significant suggesting that different cultivars do better in different locations (table 5). There as a fairly large difference between the two Kent growers. However, the temperature data were taken from the nearest meteorological office station rather than on the farm and it is likely that this may account for the differences. Also, the two sites had differences in topography.

Table 5 Fixed effects and their significance for the 3 models of chilling accumulation

		Lantin		**Jones**		**generalized Jones**	
	Df	Chisq	Pr(>Chisq)	Chisq	Pr(>Chisq)	Chisq	Pr(>Chisq)
Cultivar	5	1490.2	<2.20E-06	3424.4	<2.20E-06	3424.4	<2.20E-06
Location	2	25. 6	2.76E-06	58.1	2.42E-13	58.1	2.42E-13
Cultivar:Location	5	61.1	7.27E-12	67.5	3.47E-13	67.5	3.47E-13

There is considerable residual deviance in the model which remains somewhat overdispersed (see Table 4). However, the inclusion of sampling date in the generalized linear model of the 2015/16 data was significant (Chi-sq(1)=77.59, $p<0.00001$) and somewhat reduced the bias in the residuals (Figure 2). This suggests that the time at which chilling occurs may be important or that photo-period may have an influence on bud break. Figure 3 shows the model fit for the generalized Jones model using date as covariate the model fit against the raw data is shown in figure C1 in the appendix. The bud break later in the season in Dundee is somewhat underestimated, particularly for Ben Klibreck, but estimates for Kent and Herefordshire are rather better. In general, in the case of Ben Tirran, Dundee has greater bud break than Herefordshire or Kent towards the end of the season and for Ben Gairn Herefordshire has lower bud break than Dundee or Kent. For Ben Starav and Ben Hope there is little difference between the three locations.

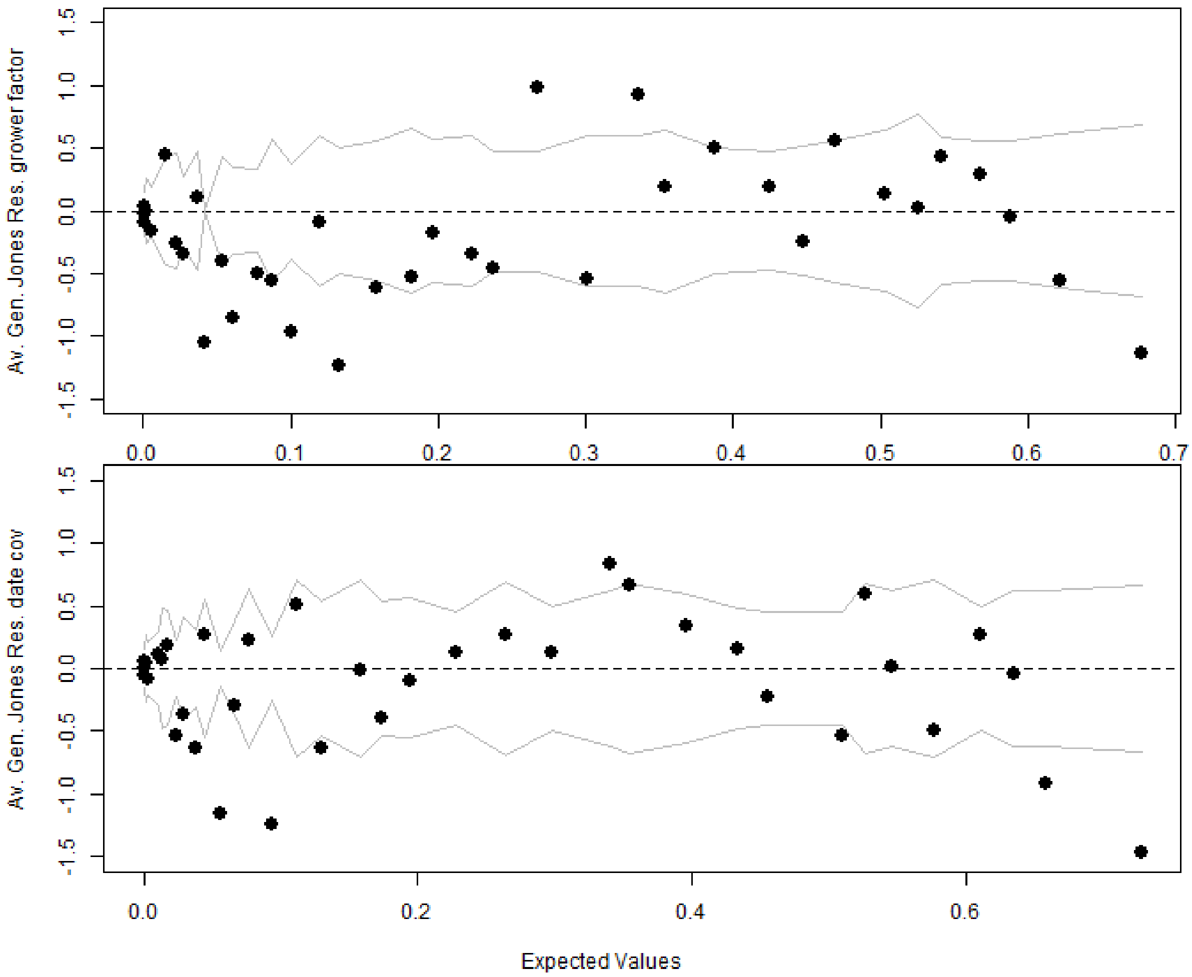

Figure 2 Binned residuals for the generalized Jones model when grower is a random factor(top) and when date is included as a covariate (bottom). The points are the average residuals for each fitted value and the grey lines the boundaries in which 95% of values would be expected to lie if the model is appropriate.

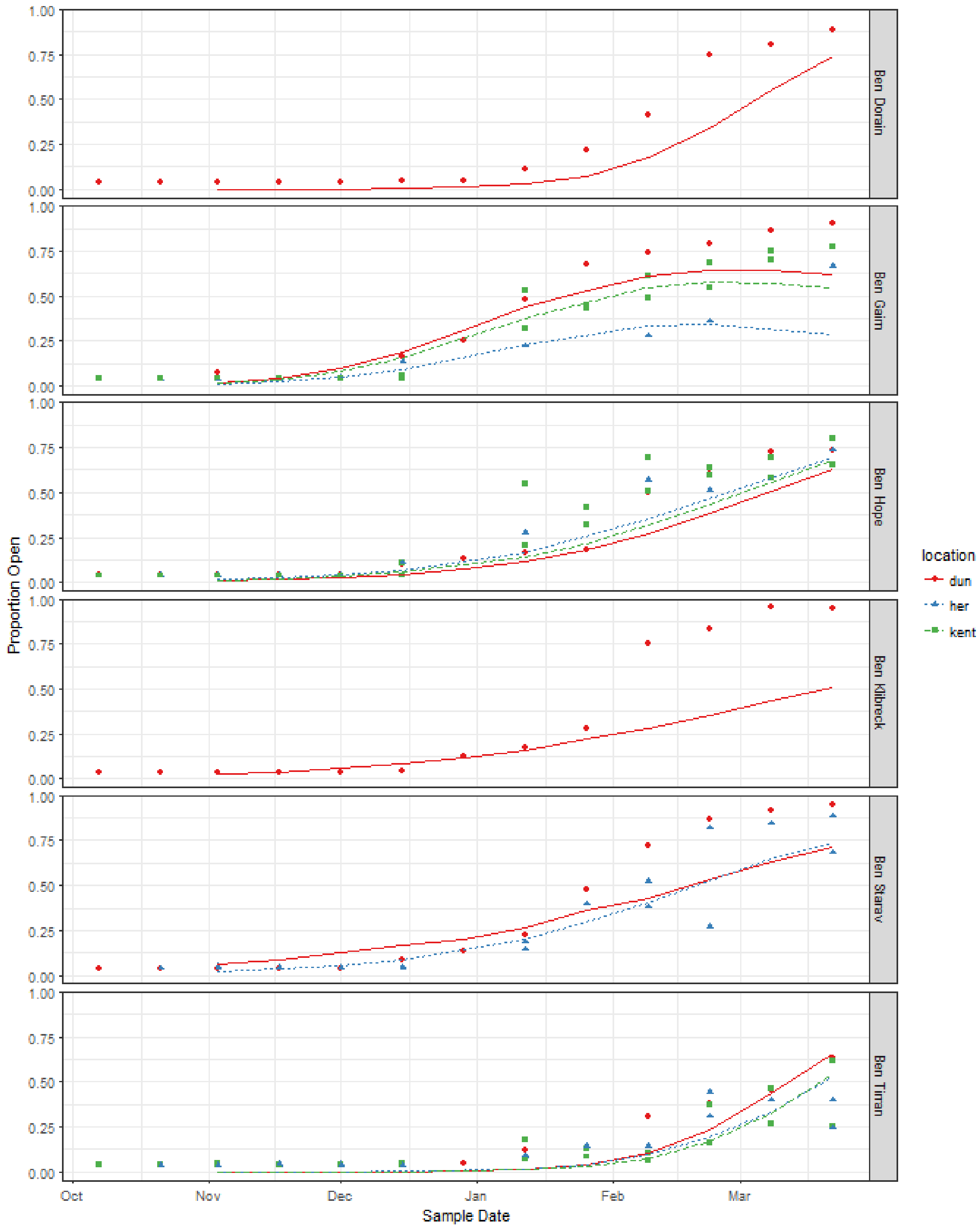

Figure 3 The fit for the Generalized Jones Model when date is included as a covariate. Points are the mean observed proportion open, red circles and solid lines are from Dundee, blue triangles and dotted lines are from Herefordshire and green squares and dashed lines are from Kent.

E Discussion

The majority of studies on bud break in winter dormant woody crops have been solely concerned with the date of bud break or flowering (often expressed at the date of 50% achievement of the appropriate phenological stage (Weinberger, 1950; Lantin 1977; Richardson et al 1974; Sunley et al 2006). Here we consider the progress of dormancy release during the season as chill accumulates expressed in terms of the final proportion of bud burst after saturating exposure of blackcurrant cuttings to a permissive temperature that allows optimal bud break. Previous work has shown that a chill function that weights lower temperatures more heavily than warmer temperatures (such as Lantin's (1977) or other exponential functions (Jones et al 2014) provides the best fit to bud burst data in blackcurrant. Earlier work indicated that in some cultivars excessive chill accumulation can even act to inhibit bud burst (Jones et al. 2013). A similar effect of excess chilling in blackcurrant has also been reported by Sønsteby and Heide (2014a; 2016), a process that they termed secondary bud-dormancy as this is a term that has been well established for seeds. The model of chill effectiveness that was used to account for this effect by Jones et al. (2013) was a symmetric quadratic function of chill accumulation. Here we demonstrate that an asymmetric function in which maximum achievable proportion of budbreak as well as the actual proportion realised was related to temperature, the generalized Jones model, gave an even better fit to the data. These results confirmed that some cultivars have an optimum chilling range, meaning that it is possible to have supra- as well as sub-optimal chilling and that maximum bud break is related to temperatures experienced as well as overall chilling accumulation.

The significance of the difference between the effect of chilling accumulation (b_1 in the models) between cultivars suggests that some cultivars will be more suited to climates where overall chilling across the winter is higher or lower, confirming that there is scope for breeders to select appropriately-adapted future cultivars on that basis. The difference between the *k*'s - temperature weightings in the quadratic term which control the relationship between maximum achievable effectiveness and temperature - suggests that some cultivars will be more affected by warm temperatures, failing to achieve full bud break in warmer winters, whilst others are more resilient to variable winters being better able to trade off between longer chilling times and warmer temperatures. In the field data, the only cultivar planted in more than one location that had a significant *k* was Ben Gairn. The winter in 2015/2016 was relatively warm and Ben Gairn did better in Dundee and Kent, which had a colder winter than in Herefordshire, although Ben Gairn is regarded as having a lower chilling requirement compared to the other cultivars used in this work. It is an early-flowering and ripening cultivar, but this can leave it vulnerable to spring frost damage at flowering time. Conversely, at the time of its release in the late 1980s Ben Tirran was intended as a late-flowering and ripening cultivar to spread the harvest season and avoid the most damaging spring frosts, but the trend towards warmer winters in the UK has now rendered it highly vulnerable to chill-related problems. Overall, with the warm winter in this study, Ben Tirran and Ben Hope had low bud break compared to the other cultivars, which is related to the relatively small value of *a* – the primary temperature weighting in both the linear and quadratic terms of the chilling models. Ben Tirran in particular is regarded as having a high chilling requirement; it is the latest of all the UK commercial blackcurrant cultivars, in terms of bud break, flowering and harvest date. The emerging problems with lack of winter chilling in Ben Tirran and other cultivars evidenced in recent warm winters in the UK have led to growers looking to exogenously applied agents to enhance bud break, together with the growing of cultivars with lower chilling requirement (such as Ben Gairn).

It is notable that these experiments were based on studies of chill response of shoots excised from plants in early October. Although there is a possibility that such excised shoots may behave differently in their chill responses than whole plants, our unpublished data, and results from Sønsteby and Heide (2014b), confirm that excised shoots can be representative of whole rooted plants.

Whilst there remains considerable unexplained variation, the models explain the proportion of the variation related to chill accumulation. Lack of systematic patterns in the residuals validates the model form and it is clear that the quadratic forms of the models avoid these patterns in both the controlled environment and field data which the linear model did not. In the field data there remains some over-estimation of bud break at low chilling accumulations and an under-estimation at mid-levels. One complication that was not accounted for by the present models is the evidence that the timing of chill also affects its effectiveness at stimulating bud burst, with Jones et al. (2013) showing that earlier chill tended to be more effective than later chill at satisfying the chill requirement. Another possibility that the present model does not incorporate is possible negation of chill by warm periods, as in the dynamic chill models (Erez et al. 1979; Fishman et al., 1987). Further experiments will be needed to disentangle the influence of the timing of chill, sequences of warm and chill and possible photo-period effects.

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Appendix

A Summary of Cuttings from Growers

Table A1 The number of cuttings received from growers, classified by cultivar

	Ben Dorain	Ben Gairn	Ben Hope	Ben Klibreck	Ben Starav	Ben Tirran
Scotland	132	132	132	132	132	132
Herefordshire 1	0	78	78	0	0	78
Herefordshire 2	0	72	72	0	0	72
Kent 1	0	46	46	0	46	46
Kent 2	0	0	0	0	66	66

Table A2 The number of cuttings received classified by cultivar and date

	Ben Dorain	Ben Gairn	Ben Hope	Ben Klibreck	Ben Starav	Ben Tirran
07/10/2015	6	12	12	6	6	12
21/10/2015	6	24	24	6	18	30
03/11/2015	6	24	24	6	18	30
17/11/2015	6	24	24	6	18	30
01/12/2015	12	30	30	12	24	36
15/12/2015	12	33	33	12	24	39
29/12/2015	12	12	12	12	12	12
12/01/2016	12	28	28	12	22	34
26/01/2016	12	24	24	12	18	30
09/02/2016	12	28	28	12	22	34
23/02/2016	12	31	31	12	22	37
08/03/2016	12	27	27	12	18	33
22/03/2016	12	31	31	12	22	37

B Calibration Model Fits

B.1 Lantin model :

```
Call:
gnm(formula = cbind(Total_Buds, No_bud) ~ Genotype +
eff.fnc.lantin.gnm(Days_Chilling,
    Temp, Genotype), family = binomial, data = dred, start = cbasered[1:54],
tolerance = 1e-10, iterMax = 3e+05, ridge = 1)

Deviance Residuals:
    Min        1Q    Median       3Q      Max
-6.9899  -1.4537  -0.2927   1.0565   5.4557

Coefficients:
                          Estimate Std. Error z value Pr(>|z|)
(Intercept)              -2.658279   0.214480 -12.394  < 2e-16 ***
Genotype'9137-2'          0.052925   0.303996   0.174 0.861789
Genotype'9521-2'          0.464011   0.293662   1.580 0.114087
Genotype'9559-6'          0.421299   0.292464   1.441 0.149722
Genotype'Amos Black'      0.657068   0.301020   2.183 0.029050 *
Genotype'Andega'          1.022019   0.283364   3.607 0.000310 ***
Genotype'Avon'           -1.213590   0.352923  -3.439 0.000585 ***
Genotype'B1834'          -0.647887   0.331511  -1.954 0.050661 .
Genotype'Baldwin'         1.333217   0.271652   4.908 9.21e-07 ***
Genotype'Brodtorp'        1.263135   0.279764   4.515 6.33e-06 ***
Genotype'Dorain'         -0.382999   0.316739  -1.209 0.226589
Genotype'Gairn'           1.067936   0.282244   3.784 0.000154 ***
Genotype'Hedda'          -0.300973   0.313853  -0.959 0.337578
Genotype'Hope'            1.280890   0.281761   4.546 5.47e-06 ***
Genotype'Lomond'          0.755916   0.283543   2.666 0.007677 **
Genotype'Pilot Mamkin'    0.921075   0.287118   3.208 0.001337 **
Genotype'Tirran'         -0.094219   0.306386  -0.308 0.758450
```

Genotype'Vane'	0.735134	0.286243	2.568	0.010222	*
b1Genotype'9134-7'	0.028378	0.002498	11.359	< 2e-16	***
b1Genotype'9137-2'	0.023850	0.002349	10.155	< 2e-16	***
b1Genotype'9521-2'	0.028648	0.002474	11.581	< 2e-16	***
b1Genotype'9559-6'	0.021423	0.002258	9.489	< 2e-16	***
b1Genotype'Amos Black'	0.010216	0.002064	4.950	7.41e-07	***
b1Genotype'Andega'	0.011436	0.002016	5.674	1.39e-08	***
b1Genotype'Avon'	0.047942	0.003568	13.437	< 2e-16	***
b1Genotype'B1834'	0.025888	0.002591	9.993	< 2e-16	***
b1Genotype'Baldwin'	0.006769	0.002108	3.211	0.001323	**
b1Genotype'Brodtorp'	0.012451	0.002072	6.010	1.86e-09	***
b1Genotype'Dorain'	0.038030	0.002916	13.042	< 2e-16	***
b1Genotype'Gairn'	0.025852	0.002630	9.829	< 2e-16	***
b1Genotype'Hedda'	0.029057	0.002650	10.964	< 2e-16	***
b1Genotype'Hope'	0.017065	0.002241	7.615	2.63e-14	***
b1Genotype'Lomond'	0.022306	0.002344	9.518	< 2e-16	***
b1Genotype'Pilot Mamkin'	0.027889	0.002425	11.503	< 2e-16	***
b1Genotype'Tirran'	0.029450	0.002567	11.472	< 2e-16	***
b1Genotype'Vane'	0.022023	0.002032	10.838	< 2e-16	***
aGenotype'9134-7'	-0.099822	0.009855	-10.129	< 2e-16	***
aGenotype'9137-2'	-0.089705	0.010916	-8.218	< 2e-16	***
aGenotype'9521-2'	-0.094894	0.009522	-9.965	< 2e-16	***
aGenotype'9559-6'	-0.101968	0.012612	-8.085	< 2e-16	***
aGenotype'Amos Black'	-0.040268	0.016844	-2.391	0.016818	*
aGenotype'Andega'	-0.091001	0.020977	-4.338	1.44e-05	***
aGenotype'Avon'	-0.107842	0.007329	-14.715	< 2e-16	***
aGenotype'B1834'	-0.086230	0.010676	-8.077	< 2e-16	***
aGenotype'Baldwin'	-0.151461	0.047451	-3.192	0.001413	**
aGenotype'Brodtorp'	-0.105318	0.021678	-4.858	1.18e-06	***
aGenotype'Dorain'	-0.099069	0.007857	-12.610	< 2e-16	***
aGenotype'Gairn'	-0.146594	0.014927	-9.821	< 2e-16	***

```
aGenotype'Hedda'          -0.110363   0.010689 -10.325  < 2e-16 ***
aGenotype'Hope'           -0.101704   0.016428  -6.191 5.98e-10 ***
aGenotype'Lomond'         -0.127844   0.014309  -8.934  < 2e-16 ***
aGenotype'Pilot Mamkin'   -0.082963   0.009093  -9.124  < 2e-16 ***
aGenotype'Tirran'         -0.103266   0.009854 -10.480  < 2e-16 ***
aGenotype'Vane'           -0.047806   0.007748  -6.170 6.83e-10 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

Residual deviance: 4779 on 1367 degrees of freedom
AIC: 7542
```

B.2 Jones model:

```
Call:
gnm(formula = cbind(Total_Buds, No_bud) ~ Genotype +
eff.fnc.gnm(Days_Chilling,     Temp, Genotype), family = binomial, data =
dred, start = cbasered,
    tolerance = 1e-10, iterMax = 3e+05, ridge = 1)

Deviance Residuals:
    Min        1Q    Median       3Q       Max
-5.4990  -1.1126  -0.1699   1.0544   5.0970

Coefficients:
                           Estimate Std. Error z value Pr(>|z|)
(Intercept)               -4.664e+00  3.909e-01 -11.934  < 2e-16 ***
```

Genotype'9137-2'	7.924e-02	5.589e-01	0.142	0.887260	
Genotype'9521-2'	1.449e+00	4.967e-01	2.917	0.003536	**
Genotype'9559-6'	1.184e+00	5.041e-01	2.349	0.018806	*
Genotype'Amos Black'	4.406e-01	5.945e-01	0.741	0.458591	
Genotype'Andega'	1.659e+00	5.014e-01	3.309	0.000936	***
Genotype'Avon'	-8.942e-02	5.640e-01	-0.159	0.874035	
Genotype'B1834'	-1.639e-01	5.928e-01	-0.276	0.782226	
Genotype'Baldwin'	2.404e+00	4.637e-01	5.184	2.17e-07	***
Genotype'Brodtorp'	2.551e+00	4.708e-01	5.418	6.01e-08	***
Genotype'Dorain'	4.326e-01	5.334e-01	0.811	0.417319	
Genotype'Gairn'	2.838e+00	4.483e-01	6.331	2.44e-10	***
Genotype'Hedda'	8.104e-01	5.215e-01	1.554	0.120218	
Genotype'Hope'	2.535e+00	4.727e-01	5.363	8.18e-08	***
Genotype'Lomond'	1.842e+00	4.746e-01	3.880	0.000104	***
Genotype'Pilot Mamkin'	1.789e+00	4.893e-01	3.656	0.000256	***
Genotype'Tirran'	1.475e-01	5.455e-01	0.270	0.786875	
Genotype'Vane'	1.129e+00	5.168e-01	2.184	0.028948	*
b1Genotype'9134-7'	7.863e-02	7.206e-03	10.912	< 2e-16	***
b1Genotype'9137-2'	7.154e-02	7.204e-03	9.932	< 2e-16	***
b1Genotype'9521-2'	5.917e-02	6.005e-03	9.853	< 2e-16	***
b1Genotype'9559-6'	5.450e-02	5.895e-03	9.245	< 2e-16	***
b1Genotype'Amos Black'	6.981e-02	9.318e-03	7.493	6.76e-14	***
b1Genotype'Andega'	4.605e-02	6.042e-03	7.620	2.53e-14	***
b1Genotype'Avon'	7.556e-02	7.782e-03	9.710	< 2e-16	***
b1Genotype'B1834'	6.097e-02	7.538e-03	8.088	< 2e-16	***
b1Genotype'Baldwin'	2.969e-02	4.982e-03	5.959	2.54e-09	***
b1Genotype'Brodtorp'	3.257e-02	5.056e-03	6.442	1.18e-10	***
b1Genotype'Dorain'	7.201e-02	6.944e-03	10.370	< 2e-16	***
b1Genotype'Gairn'	3.746e-02	4.475e-03	8.370	< 2e-16	***
b1Genotype'Hedda'	5.291e-02	6.178e-03	8.563	< 2e-16	***
b1Genotype'Hope'	4.089e-02	5.414e-03	7.553	4.26e-14	***

b1Genotype'Lomond'	5.003e-02	5.241e-03	9.545	< 2e-16	***
b1Genotype'Pilot Mamkin'	6.598e-02	6.121e-03	10.778	< 2e-16	***
b1Genotype'Tirran'	7.445e-02	6.967e-03	10.686	< 2e-16	***
b1Genotype'Vane'	6.895e-02	6.706e-03	10.283	< 2e-16	***
b2Genotype'9134-7'	-2.137e-04	2.638e-05	-8.100	< 2e-16	***
b2Genotype'9137-2'	-2.010e-04	2.714e-05	-7.405	1.31e-13	***
b2Genotype'9521-2'	-1.556e-04	2.346e-05	-6.633	3.28e-11	***
b2Genotype'9559-6'	-1.397e-04	2.164e-05	-6.456	1.07e-10	***
b2Genotype'Amos Black'	-2.664e-04	4.437e-05	-6.004	1.93e-09	***
b2Genotype'Andega'	-1.377e-04	2.488e-05	-5.534	3.13e-08	***
b2Genotype'Avon'	-1.661e-04	3.118e-05	-5.327	1.00e-07	***
b2Genotype'B1834'	-1.537e-04	2.707e-05	-5.677	1.37e-08	***
b2Genotype'Baldwin'	-7.018e-05	1.882e-05	-3.728	0.000193	***
b2Genotype'Brodtorp'	-8.264e-05	1.911e-05	-4.324	1.53e-05	***
b2Genotype'Dorain'	-1.810e-04	2.699e-05	-6.708	1.97e-11	***
b2Genotype'Gairn'	-6.794e-05	1.465e-05	-4.638	3.52e-06	***
b2Genotype'Hedda'	-1.136e-04	2.180e-05	-5.210	1.89e-07	***
b2Genotype'Hope'	-1.066e-04	2.082e-05	-5.120	3.05e-07	***
b2Genotype'Lomond'	-1.139e-04	1.818e-05	-6.262	3.80e-10	***
b2Genotype'Pilot Mamkin'	-1.915e-04	2.431e-05	-7.878	< 2e-16	***
b2Genotype'Tirran'	-1.947e-04	2.503e-05	-7.778	< 2e-16	***
b2Genotype'Vane'	-2.346e-04	2.893e-05	-8.111	< 2e-16	***
aGenotype'9134-7'	-1.270e-01	8.390e-03	-15.136	< 2e-16	***
aGenotype'9137-2'	-1.164e-01	8.921e-03	-13.046	< 2e-16	***
aGenotype'9521-2'	-1.116e-01	9.029e-03	-12.363	< 2e-16	***
aGenotype'9559-6'	-1.392e-01	1.183e-02	-11.769	< 2e-16	***
aGenotype'Amos Black'	-1.127e-01	1.082e-02	-10.420	< 2e-16	***
aGenotype'Andega'	-1.258e-01	1.377e-02	-9.130	< 2e-16	***
aGenotype'Avon'	-1.189e-01	7.632e-03	-15.578	< 2e-16	***
aGenotype'B1834'	-1.112e-01	1.057e-02	-10.522	< 2e-16	***
aGenotype'Baldwin'	-1.848e-01	2.528e-02	-7.310	2.68e-13	***

```
aGenotype'Brodtorp'      -1.355e-01  1.873e-02  -7.235 4.66e-13 ***
aGenotype'Dorain'        -1.098e-01  7.512e-03 -14.614  < 2e-16 ***
aGenotype'Gairn'         -1.745e-01  1.721e-02 -10.141  < 2e-16 ***
aGenotype'Hedda'         -1.245e-01  1.060e-02 -11.749  < 2e-16 ***
aGenotype'Hope'          -1.319e-01  1.499e-02  -8.798  < 2e-16 ***
aGenotype'Lomond'        -1.685e-01  1.402e-02 -12.012  < 2e-16 ***
aGenotype'Pilot Mamkin'  -1.135e-01  8.663e-03 -13.099  < 2e-16 ***
aGenotype'Tirran'        -1.322e-01  8.908e-03 -14.839  < 2e-16 ***
aGenotype'Vane'          -8.570e-02  7.351e-03 -11.658  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

Residual deviance: 3392.9 on 1349 degrees of freedom
AIC: 6191.9
```

B.3 Generalized Jones model:

```
Call:
gnm(formula = cbind(Total_Buds, No_bud) ~ Cultivar +
eff.fnc.all.gnm(Days_Chilling,
    Temp, Cultivar), family = binomial, data = d8, start = cba1,
    tolerance = 1e-10, iterMax = 30000, ridge = 1e-04)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-5.5811  -1.1396  -0.1421   0.9623   4.5230

Coefficients:
```

```
                          Estimate Std. Error z value Pr(>|z|)
(Intercept)             -3.998e+00  3.494e-01 -11.442  < 2e-16 ***
Cultivar'9137-2'        -7.055e-01  6.213e-01  -1.136 0.256117
Cultivar'9521-2'        -8.417e-01  6.376e-01  -1.320 0.186813
Cultivar'9559-6'         1.088e+00  4.445e-01   2.447 0.014400 *
Cultivar'Amos Black'     1.819e-01  5.369e-01   0.339 0.734717
Cultivar'Andega'         1.102e-01  5.835e-01   0.189 0.850241
Cultivar'Avon'          -6.182e-01  6.782e-01  -0.912 0.362007
Cultivar'B1834'         -3.440e-01  5.774e-01  -0.596 0.551323
Cultivar'Baldwin'        3.789e-01  5.979e-01   0.634 0.526243
Cultivar'Brodtorp'       1.313e+00  5.499e-01   2.388 0.016931 *
Cultivar'Dorain'        -4.781e-01  6.353e-01  -0.752 0.451754
Cultivar'Gairn'          6.146e-01  5.845e-01   1.051 0.293055
Cultivar'Hedda'          5.678e-01  4.875e-01   1.165 0.244110
Cultivar'Hope'           2.104e+00  4.400e-01   4.782 1.74e-06 ***
Cultivar'Klibreck'       1.782e+00  5.058e-01   3.524 0.000426 ***
Cultivar'Lomond'        -1.022e+00  6.436e-01  -1.588 0.112199
Cultivar'Pilot Mamkin'   1.339e+00  4.750e-01   2.818 0.004829 **
Cultivar'Starav'         1.069e+00  4.500e-01   2.375 0.017565 *
Cultivar'Tirran'        -6.222e-01  6.137e-01  -1.014 0.310586
Cultivar'Vane'           1.260e+00  4.311e-01   2.923 0.003470 **
b1Cultivar'9134-7'       5.872e-02  6.707e-03   8.755  < 2e-16 ***
b1Cultivar'9137-2'       7.504e-02  1.164e-02   6.447 1.14e-10 ***
b1Cultivar'9521-2'       1.065e-01  1.348e-02   7.895  < 2e-16 ***
b1Cultivar'9559-6'       3.783e-02  5.224e-03   7.242 4.43e-13 ***
b1Cultivar'Amos Black'   5.553e-02  8.753e-03   6.344 2.24e-10 ***
b1Cultivar'Andega'       7.374e-02  1.148e-02   6.424 1.33e-10 ***
b1Cultivar'Avon'         7.737e-02  1.383e-02   5.594 2.22e-08 ***
b1Cultivar'B1834'        4.804e-02  8.718e-03   5.510 3.60e-08 ***
b1Cultivar'Baldwin'      7.778e-02  1.251e-02   6.220 4.98e-10 ***
b1Cultivar'Brodtorp'     5.154e-02  1.111e-02   4.641 3.47e-06 ***
b1Cultivar'Dorain'       7.918e-02  1.320e-02   6.001 1.96e-09 ***
b1Cultivar'Gairn'        8.763e-02  1.296e-02   6.761 1.37e-11 ***
b1Cultivar'Hedda'        4.127e-02  6.624e-03   6.231 4.65e-10 ***
b1Cultivar'Hope'         3.346e-02  6.298e-03   5.313 1.08e-07 ***
```

```
b1Cultivar'Klibreck'       3.898e-02  8.978e-03   4.341 1.42e-05 ***
b1Cultivar'Lomond'         1.176e-01  1.404e-02   8.379  < 2e-16 ***
b1Cultivar'Pilot Mamkin'   5.787e-02  8.206e-03   7.052 1.77e-12 ***
b1Cultivar'Starav'         3.551e-02  4.812e-03   7.380 1.59e-13 ***
b1Cultivar'Tirran'         7.765e-02  1.194e-02   6.504 7.84e-11 ***
b1Cultivar'Vane'           4.347e-02  4.667e-03   9.314  < 2e-16 ***
b2Cultivar'9134-7'        -5.090e-05  4.358e-05  -1.168 0.242817
b2Cultivar'9137-2'        -2.245e-04  6.539e-05  -3.434 0.000595 ***
b2Cultivar'9521-2'        -4.478e-04  7.263e-05  -6.165 7.05e-10 ***
b2Cultivar'9559-6'        -1.091e-05  3.133e-05  -0.348 0.727510
b2Cultivar'Amos Black'    -1.571e-04  4.902e-05  -3.205 0.001349 **
b2Cultivar'Andega'        -3.221e-04  6.417e-05  -5.019 5.20e-07 ***
b2Cultivar'Avon'          -1.538e-04  7.378e-05  -2.084 0.037155 *
b2Cultivar'B1834'         -6.871e-05  4.541e-05  -1.513 0.130271
b2Cultivar'Baldwin'       -3.976e-04  6.972e-05  -5.703 1.18e-08 ***
b2Cultivar'Brodtorp'      -2.113e-04  6.390e-05  -3.306 0.000945 ***
b2Cultivar'Dorain'        -2.292e-04  7.789e-05  -2.943 0.003247 **
b2Cultivar'Gairn'         -3.721e-04  7.429e-05  -5.009 5.48e-07 ***
b2Cultivar'Hedda'         -3.129e-05  3.818e-05  -0.820 0.412475
b2Cultivar'Hope'          -4.957e-05  4.117e-05  -1.204 0.228499
b2Cultivar'Klibreck'      -2.403e-05  4.408e-05  -0.545 0.585681
b2Cultivar'Lomond'        -5.409e-04  7.593e-05  -7.124 1.05e-12 ***
b2Cultivar'Pilot Mamkin' -1.226e-04  5.775e-05  -2.123 0.033775 *
b2Cultivar'Starav'        -3.160e-06  1.347e-05  -0.235 0.814470
b2Cultivar'Tirran'        -2.175e-04  7.041e-05  -3.089 0.002011 **
b2Cultivar'Vane'          -1.302e-05  3.333e-05  -0.391 0.696004
aCultivar'9134-7'         -1.460e-01  9.191e-03 -15.883  < 2e-16 ***
aCultivar'9137-2'         -1.133e-01  1.201e-02  -9.430  < 2e-16 ***
aCultivar'9521-2'         -6.292e-02  8.837e-03  -7.120 1.08e-12 ***
aCultivar'9559-6'         -1.663e-01  1.410e-02 -11.793  < 2e-16 ***
aCultivar'Amos Black'     -1.207e-01  1.110e-02 -10.872  < 2e-16 ***
aCultivar'Andega'         -8.895e-02  1.311e-02  -6.783 1.17e-11 ***
aCultivar'Avon'           -4.106e-02  1.105e-02  -3.715 0.000203 ***
aCultivar'B1834'          -1.272e-01  1.399e-02  -9.091  < 2e-16 ***
aCultivar'Baldwin'        -8.934e-02  1.602e-02  -5.577 2.45e-08 ***
```

```
aCultivar'Brodtorp'      -9.737e-02  2.103e-02  -4.629 3.68e-06 ***
aCultivar'Dorain'        -1.031e-01  1.219e-02  -8.459  < 2e-16 ***
aCultivar'Gairn'         -5.258e-02  9.436e-03  -5.572 2.52e-08 ***
aCultivar'Hedda'         -1.410e-01  1.296e-02 -10.884  < 2e-16 ***
aCultivar'Hope'          -1.474e-01  1.811e-02  -8.136  < 2e-16 ***
aCultivar'Klibreck'      -6.136e-02  2.176e-02  -2.820 0.004807 **
aCultivar'Lomond'        -8.060e-02  9.662e-03  -8.342  < 2e-16 ***
aCultivar'Pilot Mamkin'  -1.200e-01  9.925e-03 -12.087  < 2e-16 ***
aCultivar'Starav'        -3.249e-02  1.582e-02  -2.053 0.040040 *
aCultivar'Tirran'        -1.292e-01  1.293e-02  -9.992  < 2e-16 ***
aCultivar'Vane'          -1.014e-01  7.722e-03 -13.126  < 2e-16 ***
kCultivar'9134-7'         6.979e-01  4.817e-01   1.449 0.147326
kCultivar'9137-2'        -3.894e-02  8.653e-02  -0.450 0.652682
kCultivar'9521-2'        -3.413e-01  4.775e-02  -7.148 8.83e-13 ***
kCultivar'9559-6'         1.210e+00  1.579e+00   0.766 0.443402
kCultivar'Amos Black'     2.163e-01  1.126e-01   1.921 0.054672 .
kCultivar'Andega'        -2.247e-01  4.061e-02  -5.532 3.17e-08 ***
kCultivar'Avon'          -1.957e+00  4.163e-01  -4.700 2.60e-06 ***
kCultivar'B1834'          3.487e-01  2.994e-01   1.165 0.244173
kCultivar'Baldwin'       -3.447e-01  3.062e-02 -11.257  < 2e-16 ***
kCultivar'Brodtorp'      -2.681e-01  6.746e-02  -3.975 7.05e-05 ***
kCultivar'Dorain'        -9.142e-02  1.146e-01  -0.797 0.425177
kCultivar'Gairn'         -6.939e-01  1.075e-01  -6.453 1.10e-10 ***
kCultivar'Hedda'          6.218e-01  6.680e-01   0.931 0.351905
kCultivar'Hope'           3.166e-01  3.814e-01   0.830 0.406358
kCultivar'Klibreck'      -2.175e+00  8.144e-01  -2.671 0.007567 **
kCultivar'Lomond'        -3.550e-01  2.868e-02 -12.378  < 2e-16 ***
kCultivar'Pilot Mamkin'   2.211e-01  2.390e-01   0.925 0.354930
kCultivar'Starav'        -6.061e+00  3.933e+00  -1.541 0.123235
kCultivar'Tirran'        -3.896e-02  9.814e-02  -0.397 0.691366
kCultivar'Vane'           2.264e+00  2.460e+00   0.921 0.357293
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)
```

```
Residual deviance: 3660.9 on 1481 degrees of freedom
AIC: 6822.1
```

B.4 Model Residuals

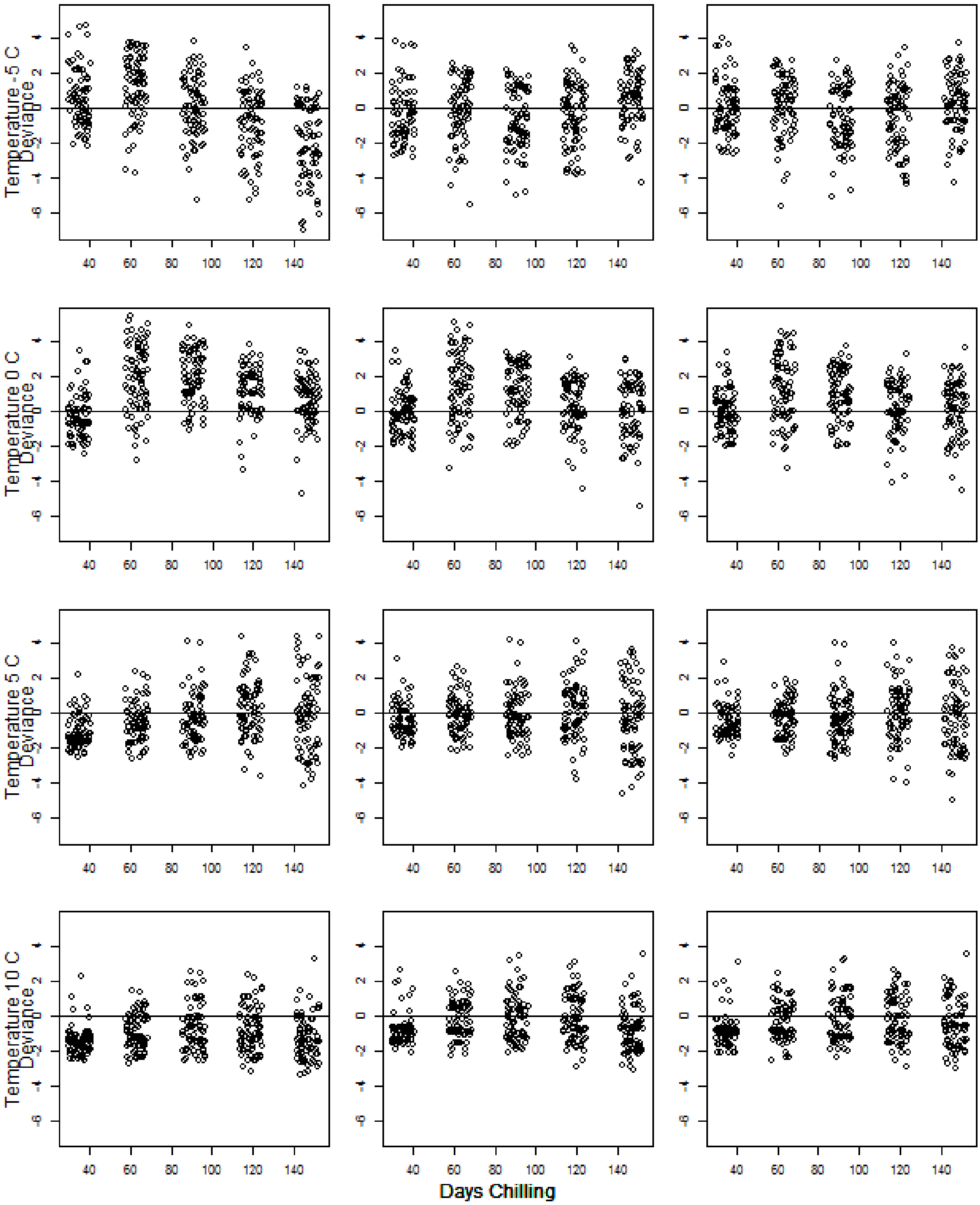


Figure B7 Residual deviances from the three models fitted to the calibration data. Column 1 shows deviances for the Lantin model, column 2 for the Jones model and column 3 for the Generalized Jones model. Row 1 shows residals for observations at -5 °C, row 2 at 0 °C, row 3 at 5 °C and the bottom row at 10 °C. The number of days chilling (35,63,91 and 119) is shown on the horizontal axes.

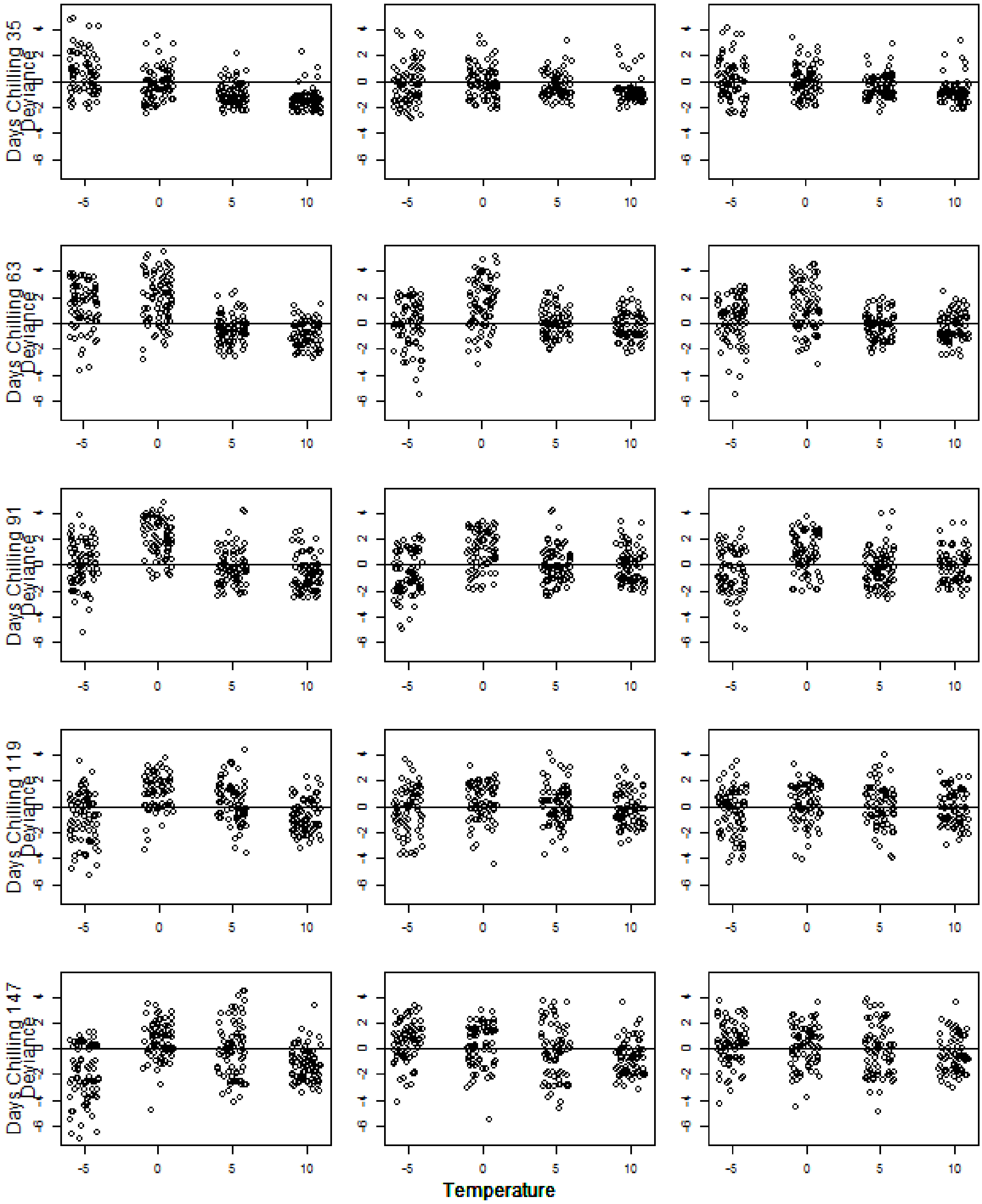


Figure B8 Residual deviances from the three models fitted to the calibration data. Column 1 shows deviances for the Lantin model, column 2 for the Jones model and column 3 for the Generalized Jones model. Row 1 shows residals for observations for 35 days chilling, row 2 for 63 days, row 3 for 91 days and the bootom row for 119 days chilling. The temperature (-5 °C, 0 °C, 5 °C and 10 °C) is shown on the horizontal axes.

C 2015/2016 Model fits

C.1 Generalized Linear Mixed Model including Grower Effect

C.1.1 Lantin model

```
Generalized linear mixed model fit by maximum likelihood (Laplace
Approximation) [glmerMod]
 Family: binomial  ( logit )
Formula: cbind(open, not.open) ~ Cultivar * location + (1 | Grower)
   Data: b
 Offset: offset.l

     AIC      BIC   logLik deviance df.resid
  6622.8   6696.2  -3297.4   6594.8     1382

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.4788 -1.2724 -0.6689  0.8857  8.8395

Random effects:
 Groups Name        Variance Std.Dev.
 Grower (Intercept) 0.01971  0.1404
Number of obs: 1396, groups:  Grower, 5

Fixed effects:
                               Estimate Std. Error z value Pr(>|z|)
(Intercept)                    -3.40206    0.15623 -21.776  < 2e-16 ***
CultivarBen Gairn               2.17796    0.08688  25.069  < 2e-16 ***
CultivarBen Hope                1.35345    0.09239  14.649  < 2e-16 ***
CultivarBen Klibreck            0.47293    0.09382   5.041 4.63e-07 ***
CultivarBen Starav              0.53045    0.08988   5.901 3.60e-09 ***
CultivarBen Tirran              0.20347    0.10078   2.019 0.043484 *
locationher                    -0.93044    0.21207  -4.387 1.15e-05 ***
locationkent                   -0.27794    0.20135  -1.380 0.167459
CultivarBen Gairn:locationher  -0.57616    0.21498  -2.680 0.007362 **
CultivarBen Hope:locationher    0.82789    0.20694   4.001 6.32e-05 ***
CultivarBen Starav:locationher  0.16096    0.15138   1.063 0.287647
```

```
CultivarBen Gairn:locationkent -0.07477    0.12871  -0.581 0.561302
CultivarBen Hope:locationkent   0.45303    0.13402   3.380 0.000724 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:
                 (Intr) CltvBG CltvBH CltvBK CltvBS CltvBT lctnhr lctnkn
CltvrBnGrn:lctnh
CultvrBnGrn      -0.346
CultivrBnHp      -0.326  0.586
CltvrBnKlbr      -0.321  0.577  0.542
CltvrBnStrv      -0.335  0.602  0.566  0.558
CltvrBnTrrn      -0.299  0.537  0.505  0.497  0.519
locationher      -0.595  0.000  0.000  0.000  0.000 -0.255
locationknt      -0.626  0.000  0.000  0.000  0.000 -0.269  0.589
CltvrBnGrn:lctnh  0.000 -0.152  0.000  0.000  0.000  0.252 -0.390 -0.125
CltvrBnHp:lctnh   0.000  0.000 -0.201  0.000  0.000  0.262 -0.405 -0.130
0.574
CltvrBStrv:       0.000  0.000  0.000  0.000 -0.248  0.357 -0.453 -0.179
0.461
CltvrBnGrn:lctnk  0.000 -0.255  0.000  0.000  0.000  0.420 -0.200 -0.423
0.300
CltvrBnHp:lctnk   0.000  0.000 -0.310  0.000  0.000  0.404 -0.192 -0.407
0.189
                 CltvrBnHp:lctnh CltBS: CltvrBnGrn:lctnk
CultvrBnGrn
CultivrBnHp
CltvrBnKlbr
CltvrBnStrv
CltvrBnTrrn
locationher
locationknt
CltvrBnGrn:lctnh
CltvrBnHp:lctnh
CltvrBStrv:       0.479
```

```
CltvrBnGrn:lctnk  0.205          0.280
CltvrBnHp:lctnk   0.335          0.269  0.636
fit warnings:
fixed-effect model matrix is rank deficient so dropping 5 columns /
coefficients
```

C.1.2 Jones Model

```
Generalized linear mixed model fit by maximum likelihood (Laplace
Approximation) [glmerMod]
 Family: binomial  ( logit )
Formula: cbind(open, not.open) ~ Cultivar * location + (1 | Grower)
   Data: b
 Offset: offset.j

     AIC      BIC   logLik deviance df.resid
  6094.3   6167.7  -3033.1   6066.3     1382

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.6223 -1.2059 -0.5241  0.8521  7.8641

Random effects:
 Groups Name        Variance Std.Dev.
 Grower (Intercept) 0.01403  0.1184
Number of obs: 1396, groups:  Grower, 5

Fixed effects:
                               Estimate Std. Error z value Pr(>|z|)
(Intercept)                    -4.47329    0.13812  -32.39  < 2e-16 ***
CultivarBen Gairn               3.13833    0.08907   35.24  < 2e-16 ***
CultivarBen Hope                1.83870    0.09502   19.35  < 2e-16 ***
CultivarBen Klibreck            0.93760    0.09657    9.71  < 2e-16 ***
CultivarBen Starav              0.69754    0.09297    7.50 6.25e-14 ***
CultivarBen Tirran             -0.02136    0.10479   -0.20 0.838515
```

```
locationher                      -1.46914    0.19463   -7.55 4.41e-14 ***
locationkent                     -0.43657    0.18154   -2.40 0.016180 *
CultivarBen Gairn:locationher    -0.17613    0.22279   -0.79 0.429210
CultivarBen Hope:locationher      1.18381    0.21684    5.46 4.78e-08 ***
CultivarBen Starav:locationher    0.54109    0.15684    3.45 0.000561 ***
CultivarBen Gairn:locationkent    0.04905    0.13259    0.37 0.711454
CultivarBen Hope:locationkent     0.56499    0.13856    4.08 4.55e-05 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:
                 (Intr) CltvBG CltvBH CltvBK CltvBS CltvBT lctnhr lctnkn
CltvrBnGrn:lctnh
CultvrBnGrn      -0.410
CultivrBnHp      -0.384  0.596
CltvrBnKlbr      -0.378  0.587  0.550
CltvrBnStrv      -0.393  0.609  0.571  0.562
CltvrBnTrrn      -0.349  0.541  0.507  0.499  0.518
locationher      -0.522  0.000  0.000  0.000  0.000 -0.291
locationknt      -0.560  0.000  0.000  0.000  0.000 -0.312  0.564
CltvrBnGrn:lctnh  0.000 -0.145  0.000  0.000  0.000  0.254 -0.452 -0.145
CltvrBnHp:lctnh   0.000  0.000 -0.193  0.000  0.000  0.261 -0.465 -0.149
0.591
CltvrBStrv:       0.000  0.000  0.000  0.000 -0.247  0.361 -0.519 -0.208
0.469
CltvrBnGrn:lctnk  0.000 -0.244  0.000  0.000  0.000  0.427 -0.230 -0.494
0.298
CltvrBnHp:lctnk   0.000  0.000 -0.303  0.000  0.000  0.409 -0.220 -0.473
0.192
                 CltvrBnHp:lctnh CltBS: CltvrBnGrn:lctnk
CultvrBnGrn
CultivrBnHp
CltvrBnKlbr
CltvrBnStrv
CltvrBnTrrn
```

```
locationher
locationknt
CltvrBnGrn:lctnh
CltvrBnHp:lctnh
CltvrBStrv:      0.482
CltvrBnGrn:lctnk  0.206           0.285
CltvrBnHp:lctnk   0.330           0.273  0.648
fit warnings:
fixed-effect model matrix is rank deficient so dropping 5 columns /
coefficients
```

C.1.3 Generalized Jones Model

```
Generalized linear mixed model fit by maximum likelihood (Laplace
Approximation) [glmerMod]
 Family: binomial  ( logit )
Formula: cbind(open, not.open) ~ Cultivar * location + (1 | Grower)
   Data: b
 Offset: offset.jg

     AIC      BIC   logLik deviance df.resid
  5913.7   5987.1  -2942.9   5885.7     1382

Scaled residuals:
    Min      1Q  Median      3Q     Max
-5.0276 -0.9991 -0.1993  0.8708 28.2248

Random effects:
 Groups Name        Variance Std.Dev.
 Grower (Intercept) 0.02146  0.1465
Number of obs: 1396, groups:  Grower, 5

Fixed effects:
                               Estimate Std. Error z value Pr(>|z|)
(Intercept)                    -10.6445     0.1680  -63.35  < 2e-16 ***
```

```
CultivarBen Gairn                4.5056     0.1001   45.01  < 2e-16 ***
CultivarBen Hope                 5.5846     0.1069   52.25  < 2e-16 ***
CultivarBen Klibreck             6.4124     0.1044   61.44  < 2e-16 ***
CultivarBen Starav               7.4100     0.1003   73.90  < 2e-16 ***
CultivarBen Tirran              -0.5731     0.1208   -4.75 2.08e-06 ***
locationher                      0.1905     0.2288    0.83 0.404985
locationkent                    -0.3443     0.2173   -1.58 0.113056
CultivarBen Gairn:locationher   -0.6945     0.2294   -3.03 0.002470 **
CultivarBen Hope:locationher     0.3298     0.2297    1.44 0.151017
CultivarBen Starav:locationher  -1.4193     0.1665   -8.52  < 2e-16 ***
CultivarBen Gairn:locationkent   0.1726     0.1463    1.18 0.238121
CultivarBen Hope:locationkent    0.5769     0.1537    3.75 0.000174 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:
                 (Intr) CltvBG CltvBH CltvBK CltvBS CltvBT lctnhr lctnkn
CltvrBnGrn:lctnh
CultvrBnGrn      -0.403
CultivrBnHp      -0.377  0.633
CltvrBnKlbr      -0.386  0.649  0.607
CltvrBnStrv      -0.402  0.675  0.632  0.647
CltvrBnTrrn      -0.334  0.561  0.525  0.538  0.560
locationher      -0.558  0.000  0.000  0.000  0.000 -0.283
locationknt      -0.588  0.000  0.000  0.000  0.000 -0.298  0.588
CltvrBnGrn:lctnh  0.000 -0.141  0.000  0.000  0.000  0.282 -0.432 -0.155
CltvrBnHp:lctnh   0.000  0.000 -0.189  0.000  0.000  0.281 -0.432 -0.155
0.583
CltvrBStrv:       0.000  0.000  0.000  0.000 -0.196  0.388 -0.505 -0.216
0.517
CltvrBnGrn:lctnk  0.000 -0.222  0.000  0.000  0.000  0.442 -0.233 -0.472
0.329
CltvrBnHp:lctnk   0.000  0.000 -0.283  0.000  0.000  0.421 -0.222 -0.449
0.221
                 CltvrBnHp:lctnh CltBS: CltvrBnGrn:lctnk
```

```
CultvrBnGrn
CultivrBnHp
CltvrBnKlbr
CltvrBnStrv
CltvrBnTrrn
locationher
locationknt
CltvrBnGrn:lctnh
CltvrBnHp:lctnh
CltvrBStrv:       0.516
CltvrBnGrn:lctnk  0.232           0.320
CltvrBnHp:lctnk   0.352           0.305  0.667
fit warnings:
fixed-effect model matrix is rank deficient so dropping 5 columns /
coefficients
```

C.2 Generalized Linear Model including date

C.2.1 Lantin Model

```
Call:
glm(formula = cbind(open, not.open) ~ Cultivar * location + date,
    family = binomial, data = b, offset = offset.l)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-5.3115  -1.1949  -0.5813   0.6866   6.4825

Coefficients: (5 not defined because of singularities)
                                   Estimate Std. Error z value Pr(>|z|)
(Intercept)                      -3.084e+02  1.039e+01 -29.677  < 2e-16 ***
CultivarBen Gairn                 2.545e+00  9.727e-02  26.161  < 2e-16 ***
CultivarBen Hope                  1.536e+00  1.009e-01  15.229  < 2e-16 ***
CultivarBen Klibreck              5.458e-01  1.034e-01   5.280 1.29e-07 ***
```

```
CultivarBen Starav                    7.517e-01  1.008e-01   7.456 8.89e-14 ***
CultivarBen Tirran                    2.127e-01  1.092e-01   1.947 0.051491 .
locationher                          -9.338e-01  1.281e-01  -7.289 3.13e-13 ***
locationkent                         -3.838e-01  1.118e-01  -3.433 0.000598 ***
date                                  1.810e-02  6.167e-04  29.359  < 2e-16 ***
CultivarBen Gairn:locationher        -8.507e-01  2.063e-01  -4.123 3.74e-05 ***
CultivarBen Hope:locationher          8.697e-01  1.958e-01   4.442 8.90e-06 ***
CultivarBen Klibreck:locationher             NA         NA      NA       NA
CultivarBen Starav:locationher        1.727e-01  1.661e-01   1.040 0.298439
CultivarBen Tirran:locationher               NA         NA      NA       NA
CultivarBen Gairn:locationkent       -7.622e-02  1.402e-01  -0.544 0.586575
CultivarBen Hope:locationkent         5.510e-01  1.443e-01   3.819 0.000134 ***
CultivarBen Klibreck:locationkent            NA         NA      NA       NA
CultivarBen Starav:locationkent              NA         NA      NA       NA
CultivarBen Tirran:locationkent              NA         NA      NA       NA
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 6537.9  on 1395  degrees of freedom
Residual deviance: 3337.5  on 1382  degrees of freedom
AIC: 5534.9

Number of Fisher Scoring iterations: 5
```

C.2.2 Jones Model

```
Call:
glm(formula = cbind(open, not.open) ~ Cultivar * location + date,
    family = binomial, data = b, offset = offset.j)
```

```
Deviance Residuals:
    Min       1Q   Median       3Q      Max
-5.1656  -1.1983  -0.4803   0.7834   6.4030

Coefficients: (5 not defined because of singularities)
                                    Estimate Std. Error z value Pr(>|z|)
(Intercept)                       -2.286e+02  1.045e+01 -21.870  < 2e-16 ***
CultivarBen Gairn                  3.456e+00  9.729e-02  35.520  < 2e-16 ***
CultivarBen Hope                   1.983e+00  1.018e-01  19.475  < 2e-16 ***
CultivarBen Klibreck               1.015e+00  1.038e-01   9.773  < 2e-16 ***
CultivarBen Starav                 8.832e-01  1.013e-01   8.716  < 2e-16 ***
CultivarBen Tirran                -5.789e-02  1.115e-01  -0.519  0.60371
locationher                       -1.475e+00  1.311e-01 -11.255  < 2e-16 ***
locationkent                      -5.259e-01  1.147e-01  -4.583 4.57e-06 ***
date                               1.331e-02  6.204e-04  21.447  < 2e-16 ***
CultivarBen Gairn:locationher     -3.887e-01  2.053e-01  -1.893  0.05832 .
CultivarBen Hope:locationher       1.177e+00  1.989e-01   5.915 3.32e-09 ***
CultivarBen Klibreck:locationher          NA         NA      NA       NA
CultivarBen Starav:locationher     5.470e-01  1.674e-01   3.268  0.00108 **
CultivarBen Tirran:locationher            NA         NA      NA       NA
CultivarBen Gairn:locationkent     5.970e-02  1.413e-01   0.422  0.67267
CultivarBen Hope:locationkent      6.407e-01  1.470e-01   4.359 1.30e-05 ***
CultivarBen Klibreck:locationkent         NA         NA      NA       NA
CultivarBen Starav:locationkent           NA         NA      NA       NA
CultivarBen Tirran:locationkent           NA         NA      NA       NA
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 8475.1  on 1395  degrees of freedom
```

```
Residual deviance: 3354.9  on 1382  degrees of freedom
AIC: 5552.3

Number of Fisher Scoring iterations: 5
```

C.2.3 Generalized Jones model

```
Call:
glm(formula = cbind(open, not.open) ~ Cultivar * location + date,
    family = binomial, data = b, offset = offset.jg)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-5.0747  -1.1681  -0.2494   0.8817   6.5527

Coefficients: (5 not defined because of singularities)
                                   Estimate Std. Error z value Pr(>|z|)
(Intercept)                      -1.049e+02  1.108e+01  -9.472  < 2e-16 ***
CultivarBen Gairn                 4.651e+00  1.042e-01  44.625  < 2e-16 ***
CultivarBen Hope                  5.656e+00  1.102e-01  51.321  < 2e-16 ***
CultivarBen Klibreck              6.520e+00  1.078e-01  60.509  < 2e-16 ***
CultivarBen Starav                7.565e+00  1.048e-01  72.174  < 2e-16 ***
CultivarBen Tirran               -5.973e-01  1.237e-01  -4.829 1.37e-06 ***
locationher                       2.659e-01  1.406e-01   1.892 0.058541 .
locationkent                     -3.840e-01  1.248e-01  -3.077 0.002092 **
date                              5.594e-03  6.572e-04   8.512  < 2e-16 ***
CultivarBen Gairn:locationher    -9.508e-01  2.063e-01  -4.608 4.06e-06 ***
CultivarBen Hope:locationher      1.231e-01  2.095e-01   0.588 0.556690
CultivarBen Klibreck:locationher         NA         NA      NA       NA
CultivarBen Starav:locationher   -1.455e+00  1.706e-01  -8.528  < 2e-16 ***
CultivarBen Tirran:locationher           NA         NA      NA       NA
CultivarBen Gairn:locationkent    1.634e-01  1.495e-01   1.093 0.274506
```

```
CultivarBen Hope:locationkent      5.983e-01  1.574e-01   3.800 0.000145 ***
CultivarBen Klibreck:locationkent         NA         NA      NA       NA
CultivarBen Starav:locationkent           NA         NA      NA       NA
CultivarBen Tirran:locationkent           NA         NA      NA       NA
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 20732.8  on 1395  degrees of freedom
Residual deviance:  3647.1  on 1382  degrees of freedom
AIC: 5844.4

Number of Fisher Scoring iterations: 5
```

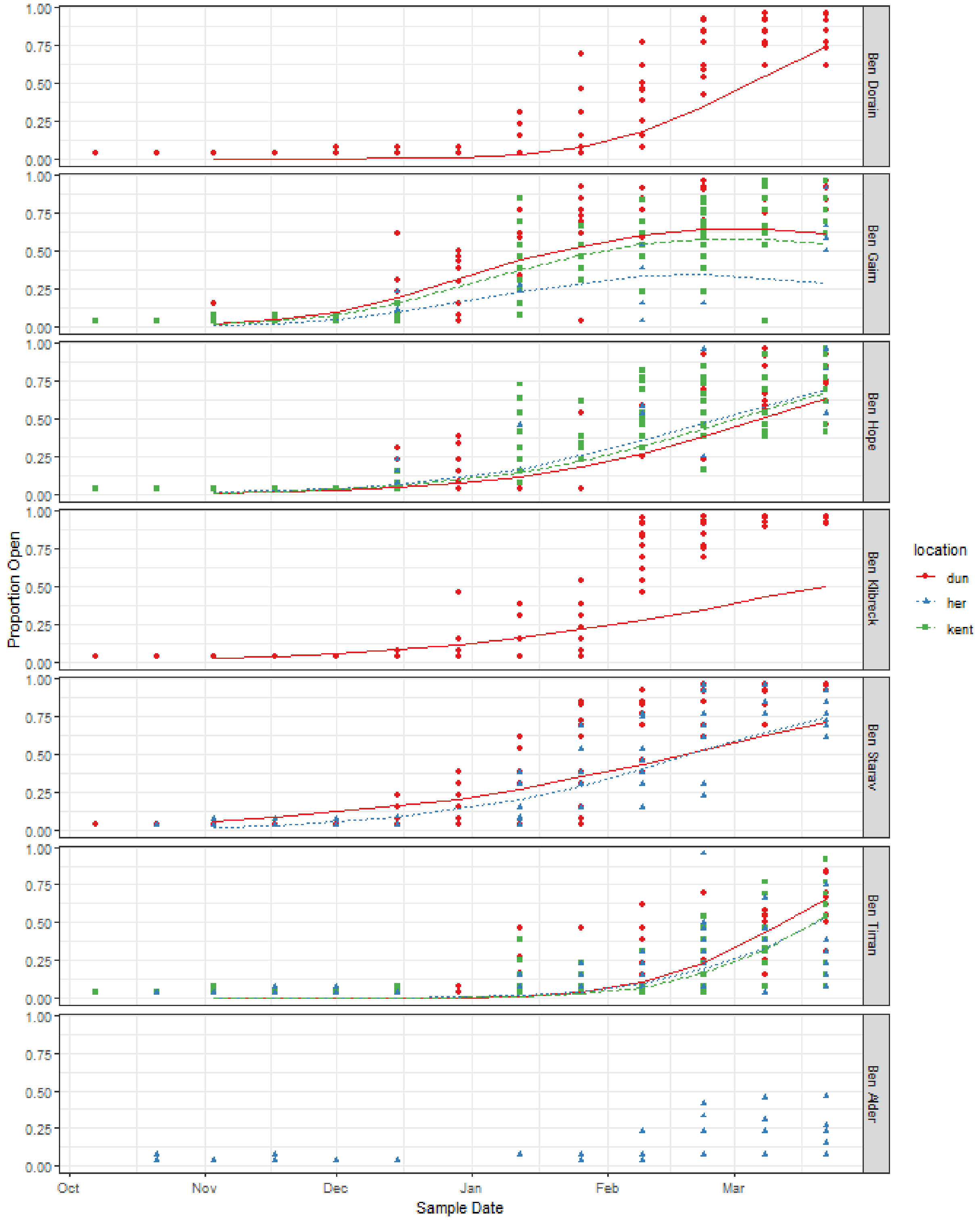


Figure C1 The fit for the Generalized Jones Model when date is included as a covariate. Points are the observed proportion open for each sample, red circles and solid lines are from Dundee, blue triangles and dotted lines are from Herefordshire and green squares and dashed

Table 1

	Optimum Chilling Time	Maximum Effectiveness max(E)
k<-0.5	Decreases	Decreases
k=-0.5	Independent	Decreases
-0.5<k<0	Increases	Decreases
k=0	Increases	Independent
k>0	Increases	Increases

Table 1 The effect of k have on the optimum chilling time and maximum achievable effectiveness

Table 2

Cultivar	k	s.e(k)
Ben Starav	-6.06	3.933
Ben Klibreck*	**-2.18**	**0.814**
Ben Avon*	**-1.96**	**0.416**
Ben Gairn*	**-0.69**	**0.108**
Ben Lomond*	**-0.36**	**0.029**
Ben Baldwin*	**-0.35**	**0.031**
9521-2*	**-0.34**	**0.048**
Ben Brodtorp*	**-0.27**	**0.067**
Ben Andega*	**-0.23**	**0.041**
Ben Dorain	-0.09	0.115
Ben Tirran	-0.04	0.098
9137-2	-0.04	0.087
Amos Black	0.22	0.113
Pilot Mamkin	0.22	0.239
Ben Hope	0.32	0.381
B1834	0.35	0.299
Ben Hedda	0.62	0.668
9134-7	0.70	0.482
9559-6	1.21	1.579
Ben Vane	2.26	2.460

Table 1 Estimated values of k for the Generalized Jones model. cultivars with a * have a value significantly different from 0 at the 95% confidence level

Table 3

Cultivar	b_1	b_2	a	k (s.e)
Ben Dorain	7.92e-02 (1.320e-02)	-2.29e-04 (7.789e-05)	-1.03e-01 (1.219e-02)	-9.14e-02 (1.146e-01)
Ben Gairn	8.76e-02 (1.296e-02)	-3.72e-04 (7.429e-05)	-5.26e-02 (9.436e-03)	-6.94e-01 (1.075e-01)
Ben Hope	3.35e-02 (6.298e-03)	-4.96e-05 (4.117e-05)	-1.47e-01 (1.811e-02)	3.17e-01 (3.814e-01)
Ben Klibreck	3.90e-02 (8.978e-03)	-2.40e-05 (4.408e-05)	-6.14e-02 (2.176e-02)	-2.18e+00 (8.144e-01)
Ben Starav	3.55e-02 (4.812e-03)	-3.16e-06 (1.347e-05)	-3.25e-02 (1.582e-02)	-6.06e+00 (3.933e+00)
Ben Tirran	7.77e-02 (1.194e-02)	-2.18e-04 (7.041e-05)	-1.29e-01 (1.293e-02)	-3.90e-02 (9.814e-02)

Table 1 parameters for the Generalized Jones model from the controlled temperature data for cultivars submitted by growers in 2015/2016

Table 4

Model	Res. Deviance	Res. d.f.	AIC
Lantin	6594.8	1382	6622.8
Jones	6066.3	1382	6094.3
Gen. Jones	5885.7	1382	5913.7

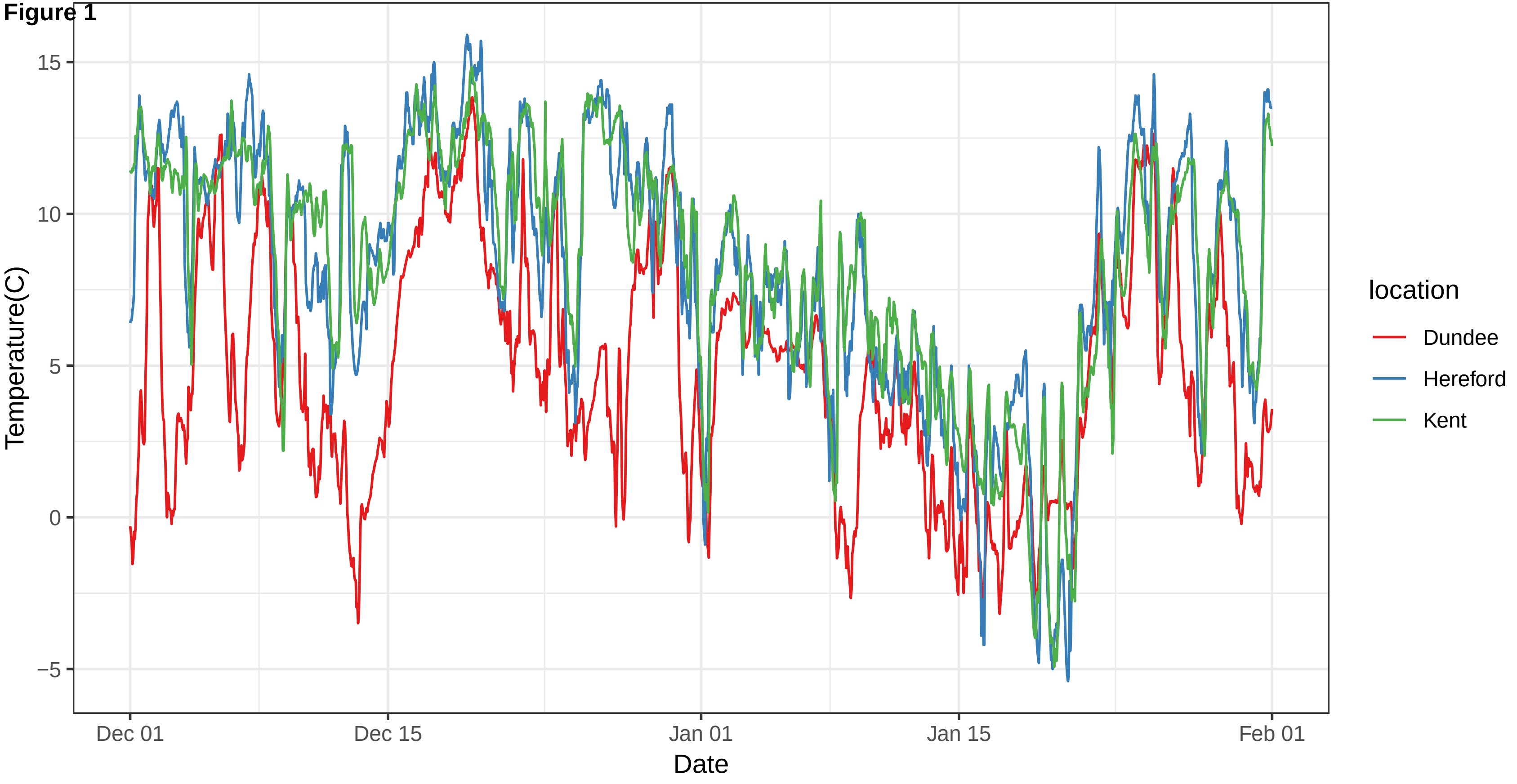
Table 1 Residual deviance and AIC for the 3 models.

Table 5

	Df	Lantin		Jones		generalized Jones	
		Chisq	Pr(>Chisq)	Chisq	Pr(>Chisq)	Chisq	Pr(>Chisq)
Cultivar	5	1490.2	<2.20E-06	3424.4	<2.20E-06	3424.4	<2.20E-06
Location	2	25. 6	2.76E-06	58.1	2.42E-13	58.1	2.42E-13
Cultivar:Location	5	61.1	7.27E-12	67.5	3.47E-13	67.5	3.47E-13

Table 1 Fixed effects and their significance for the 3 models of chilling accumulation

Figure 1



15
10
5
0
−5
Temperature(C)
Dec 01
Dec 15
Jan 01
Jan 15
Feb 01
Date
location
Dundee
Hereford
Kent

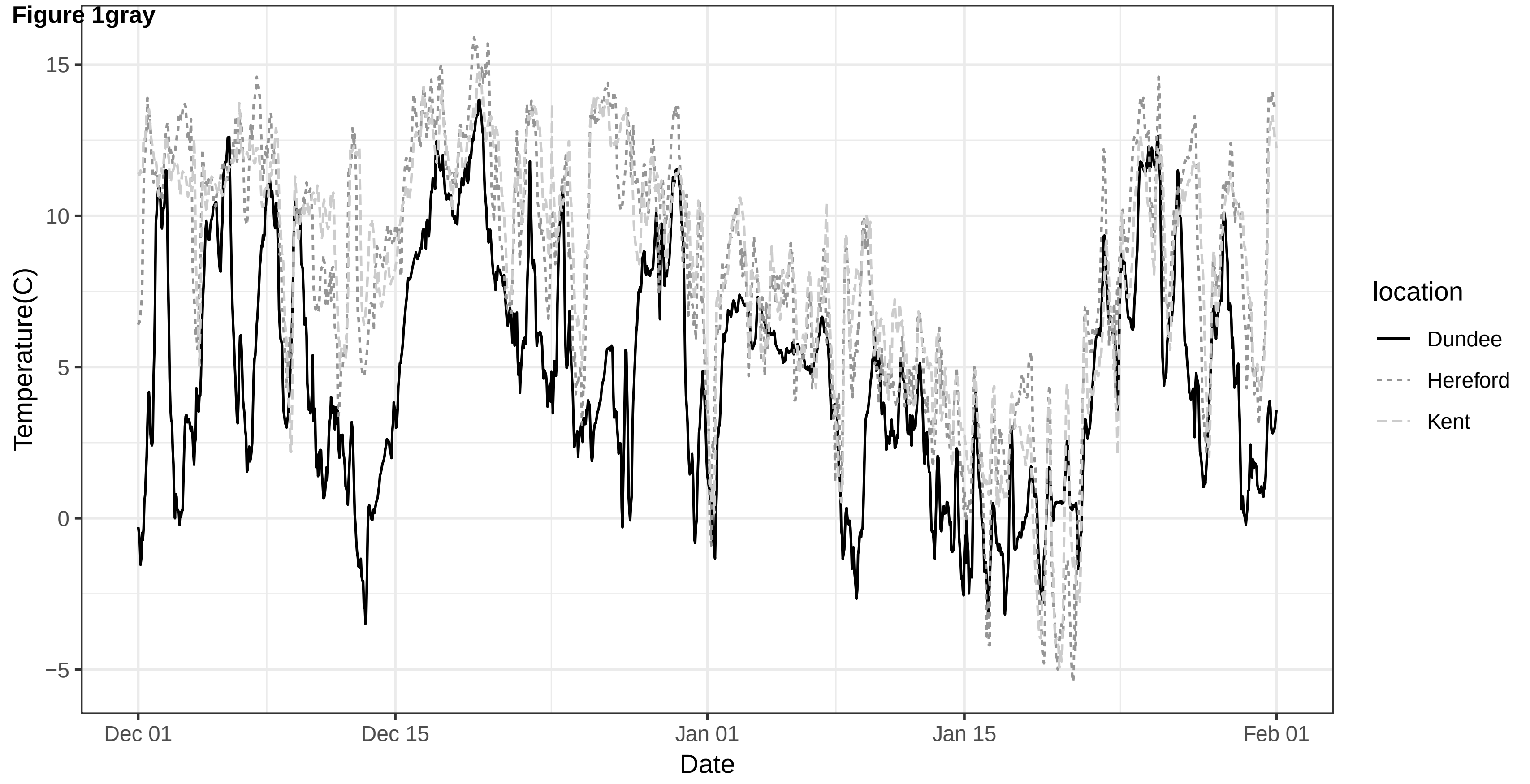
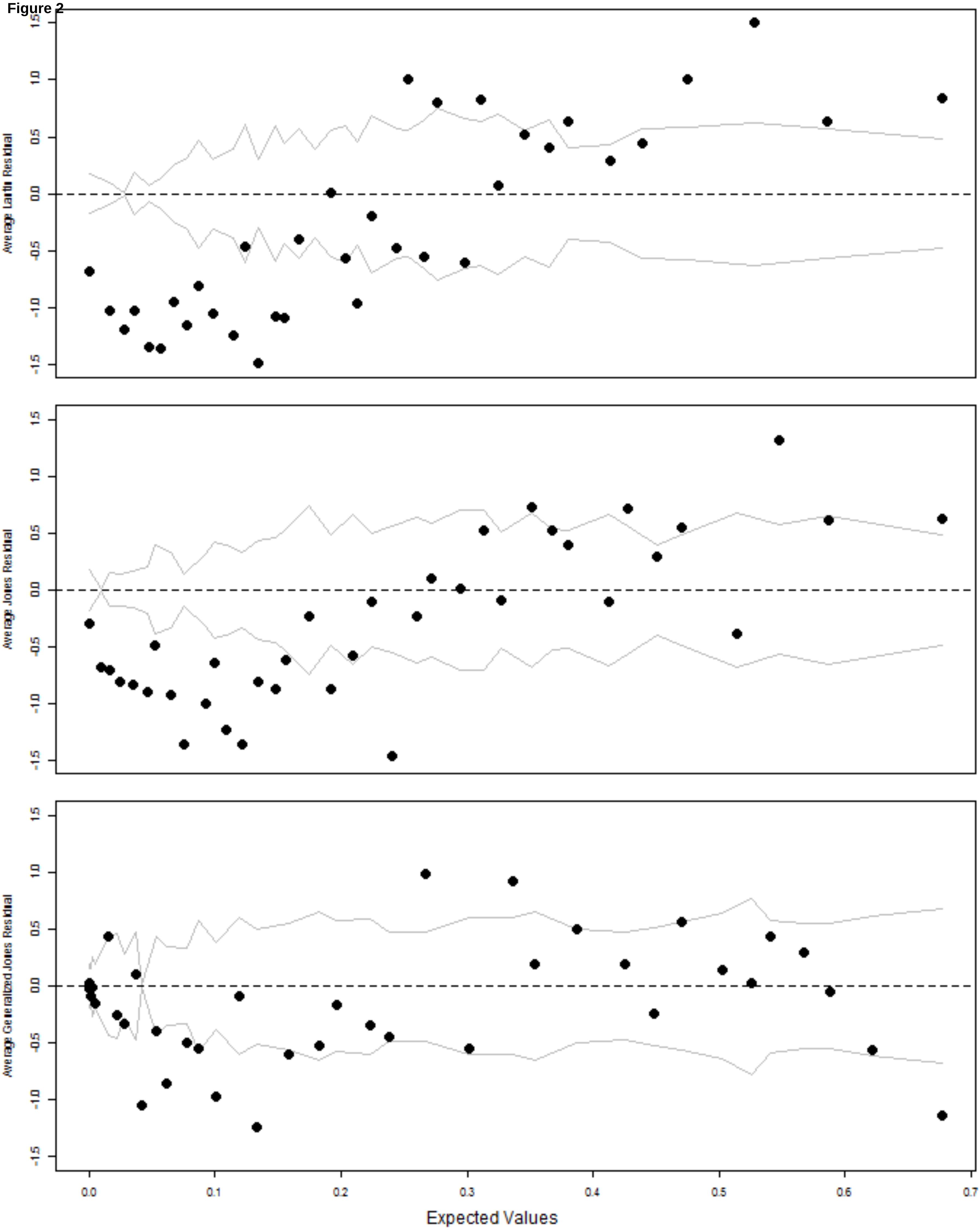


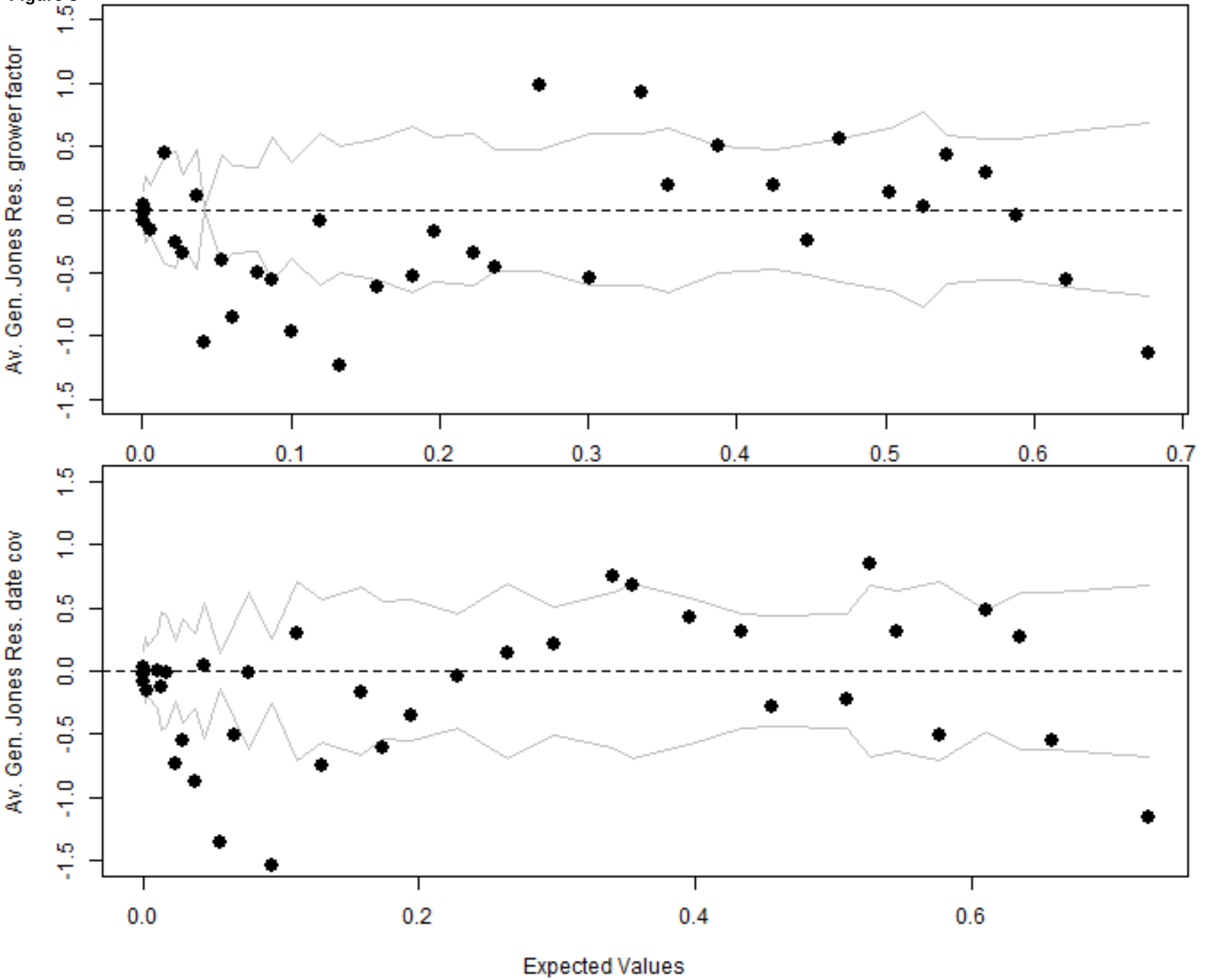
Figure 1gray
15
10
5
0
−5
Temperature(C)
Dec 01
Dec 15
Jan 01
Jan 15
Feb 01
Date
location
Dundee
Hereford
Kent

Figure 2



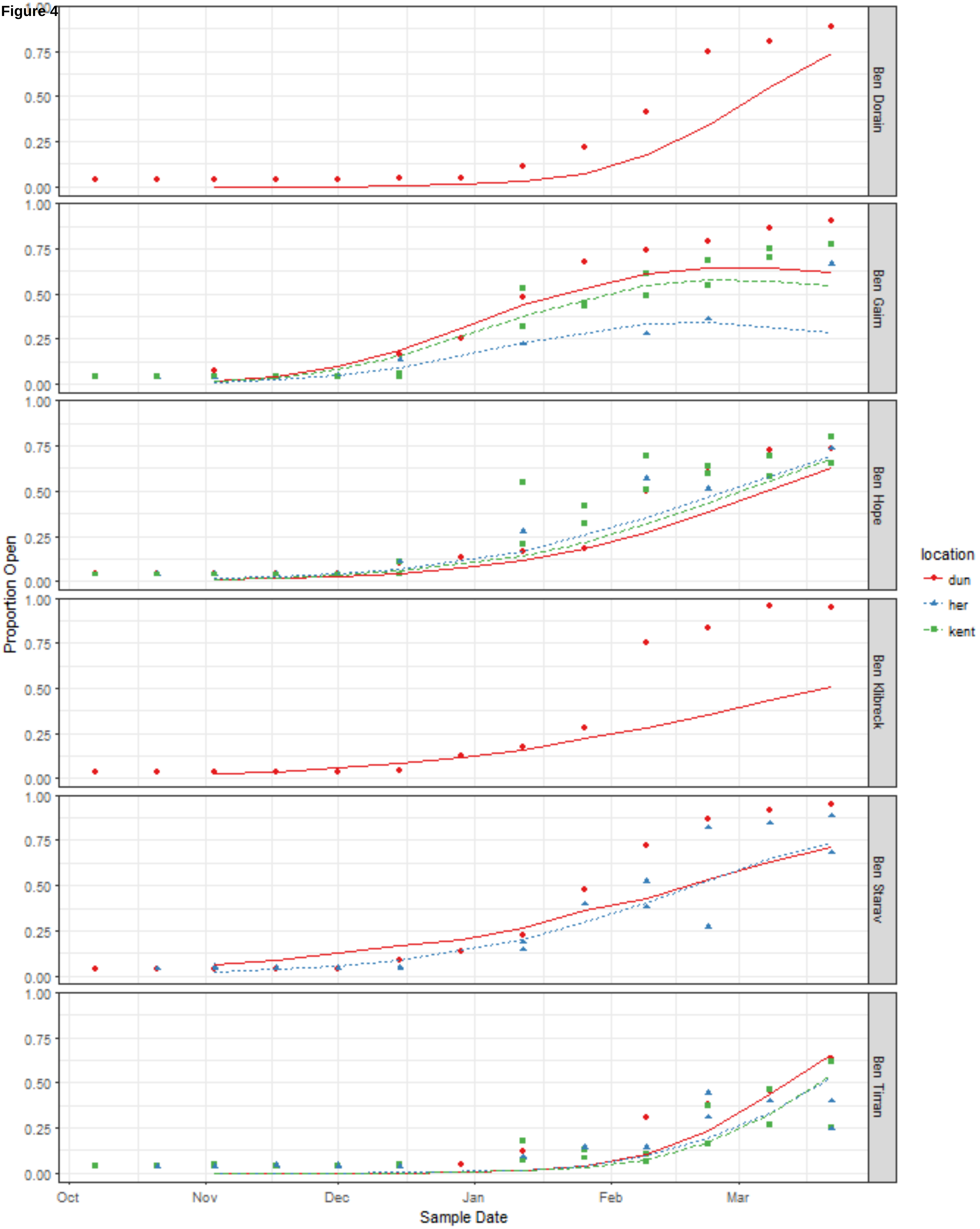
Average Larthi Residual
Average Jones Residual
Average Generalized Jones Residual
Expected Values

Figure 3



Av. Gen. Jones Res. grower factor
Av. Gen. Jones Res. date cov
Expected Values

Figure 4



Ben Dorain
Ben Gairn
Ben Hope
Ben Kilbreck
Ben Starav
Ben Tirran
Proportion Open
Sample Date
Oct
Nov
Dec
Jan
Feb
Mar
0.00
0.25
0.50
0.75
1.00
location
dun
her
kent

Figure 4gray

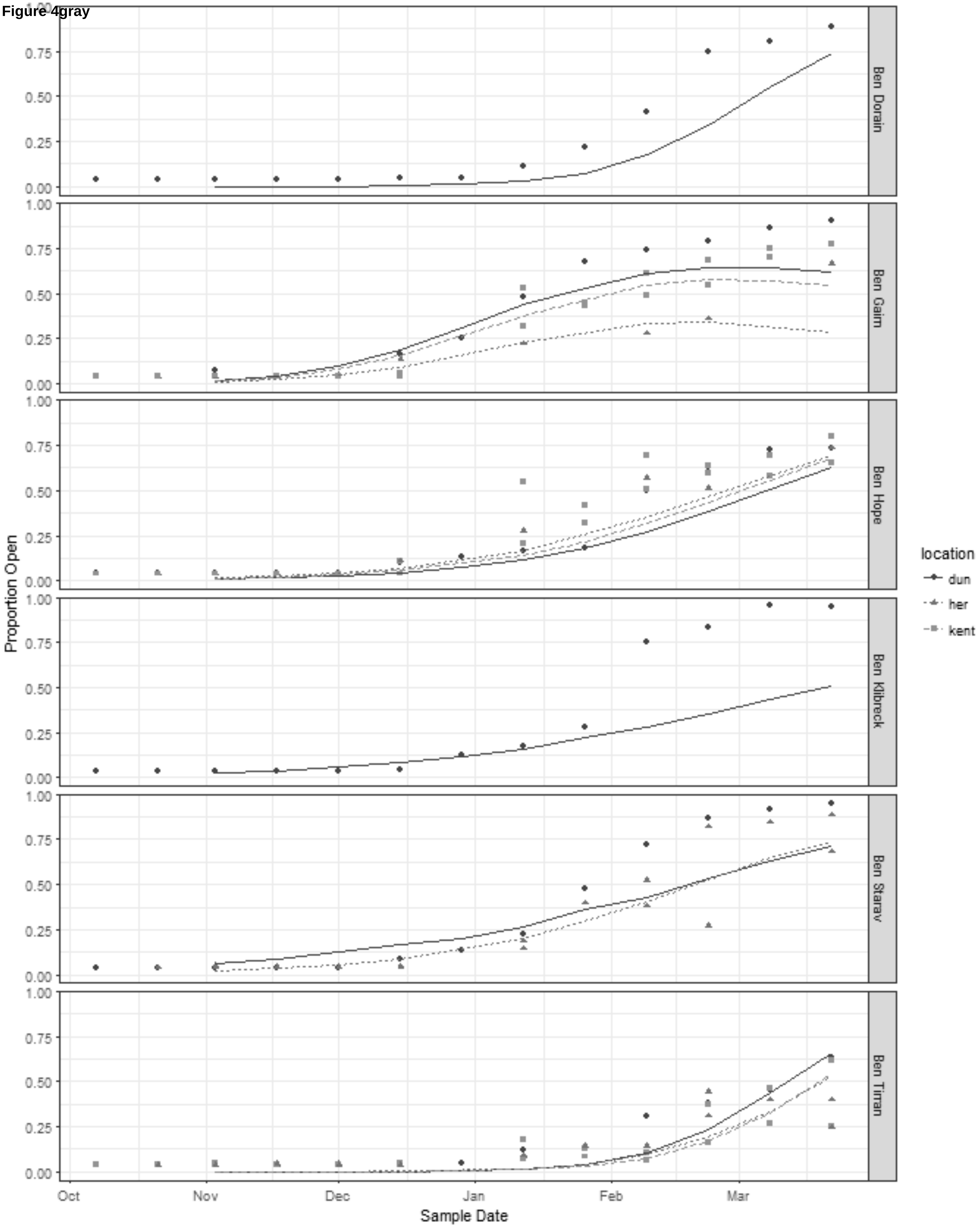


Figure C1 :Appendix [part of manuscript]

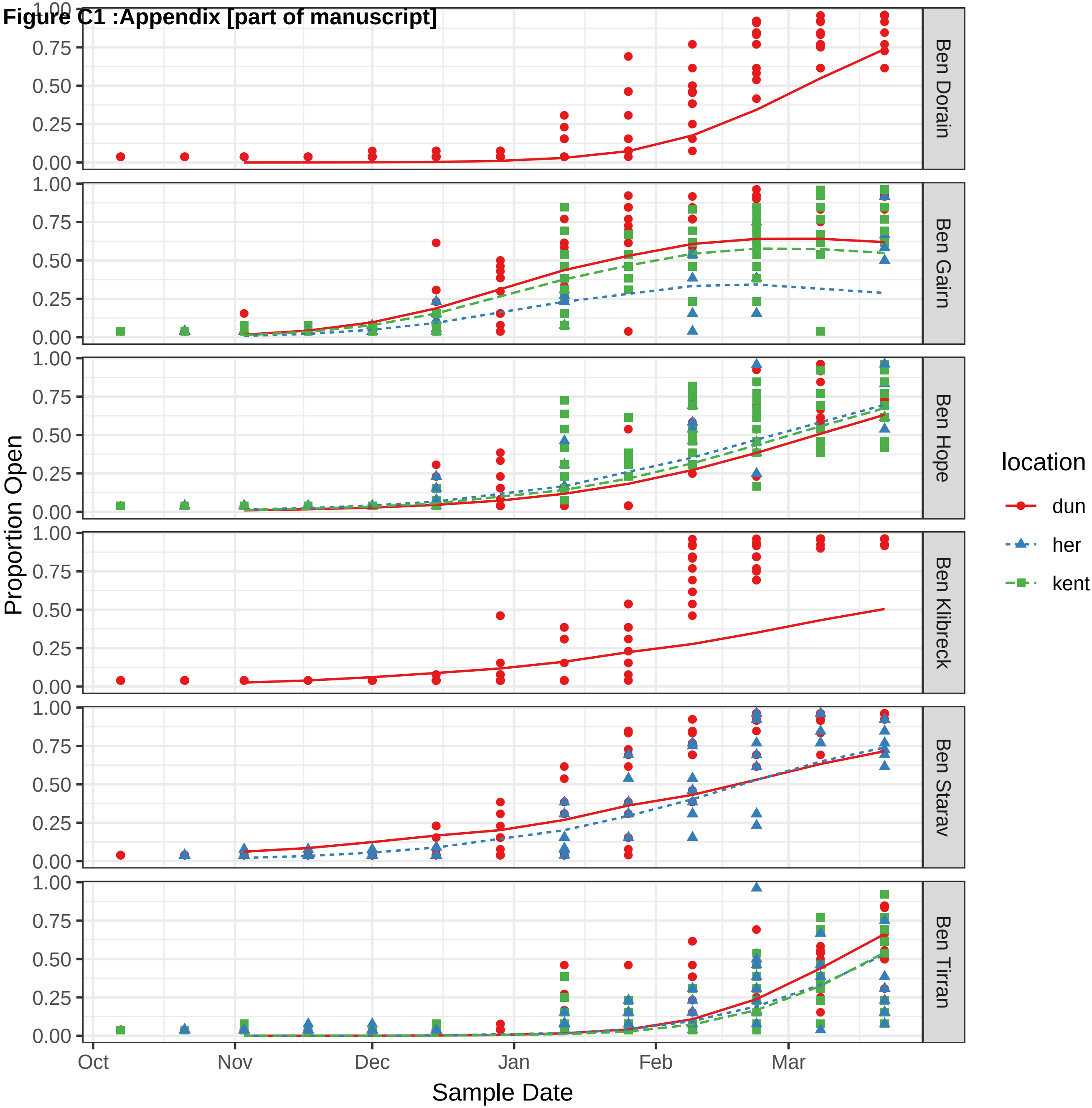
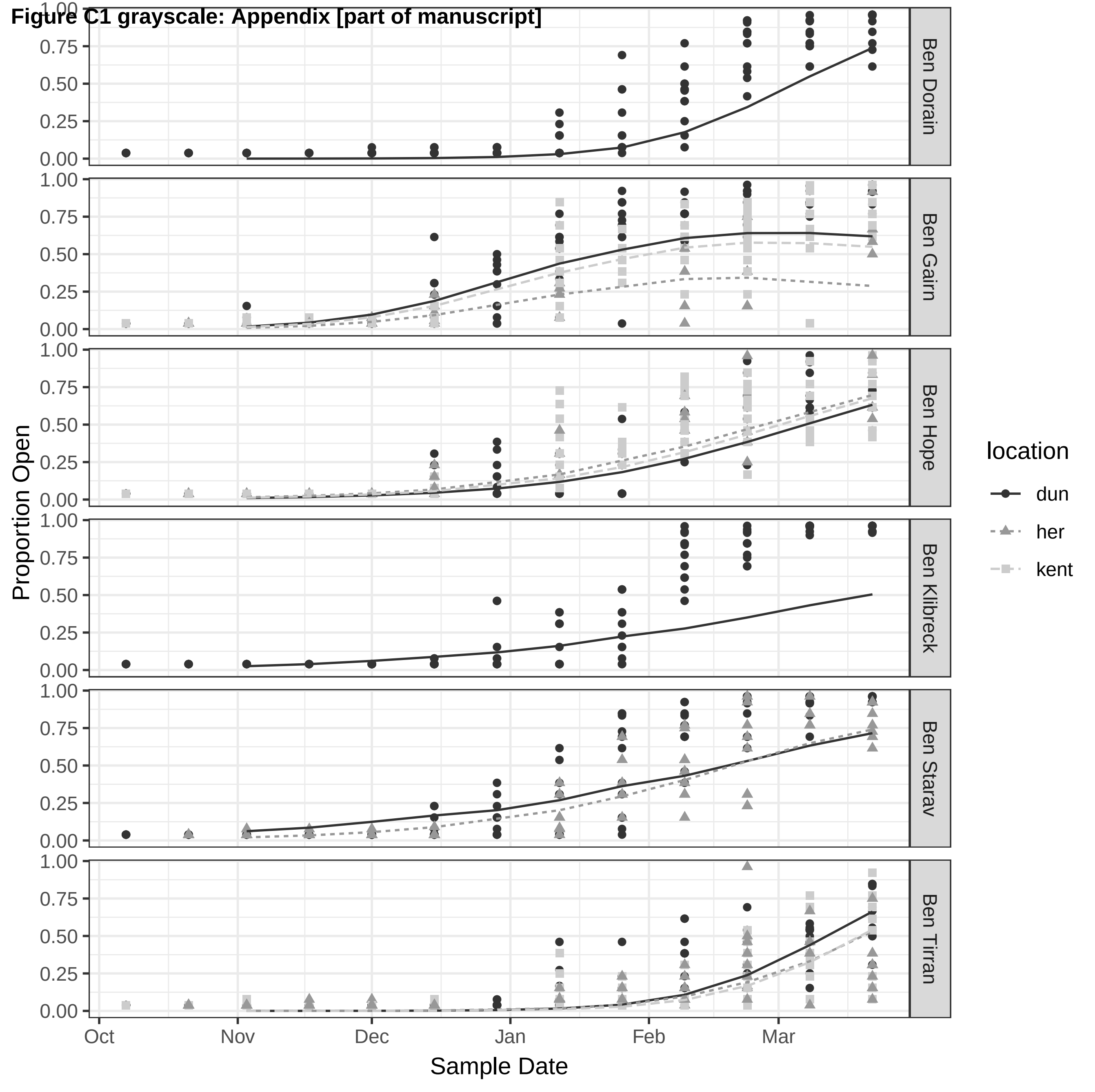


Figure C1 grayscale: Appendix [part of manuscript]



Appendix [not a part of manuscript]

S Calibration Model Fits

S.1 Lantin model :

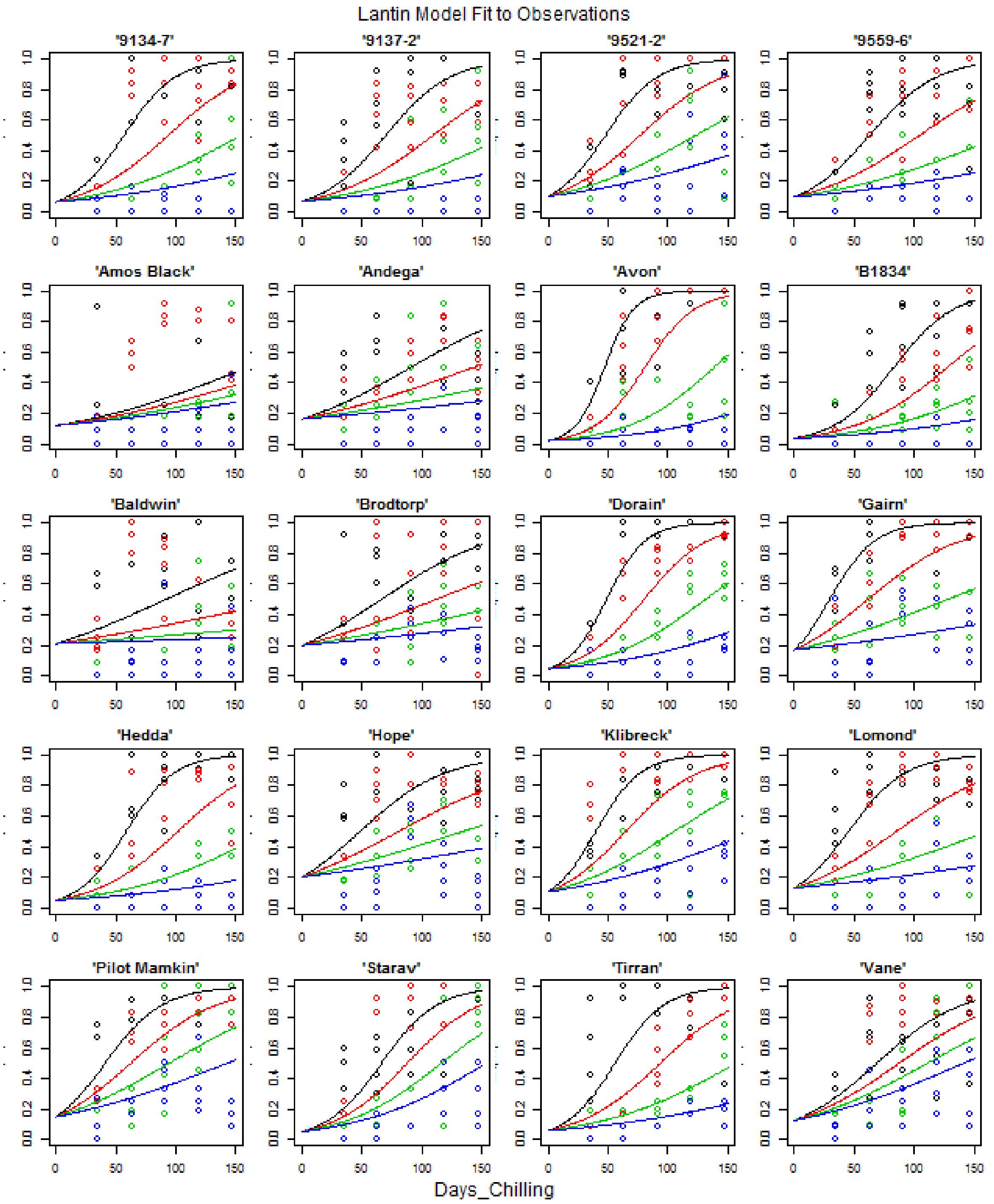


Figure S1 Proportion of buds broken at the end of the controlled data experiment. Lines represent predictions from the Lantin model and points represent observed data. Black shows outcomes at -5 °C, red 0 °C, green 5 °C and blue 10 °C.

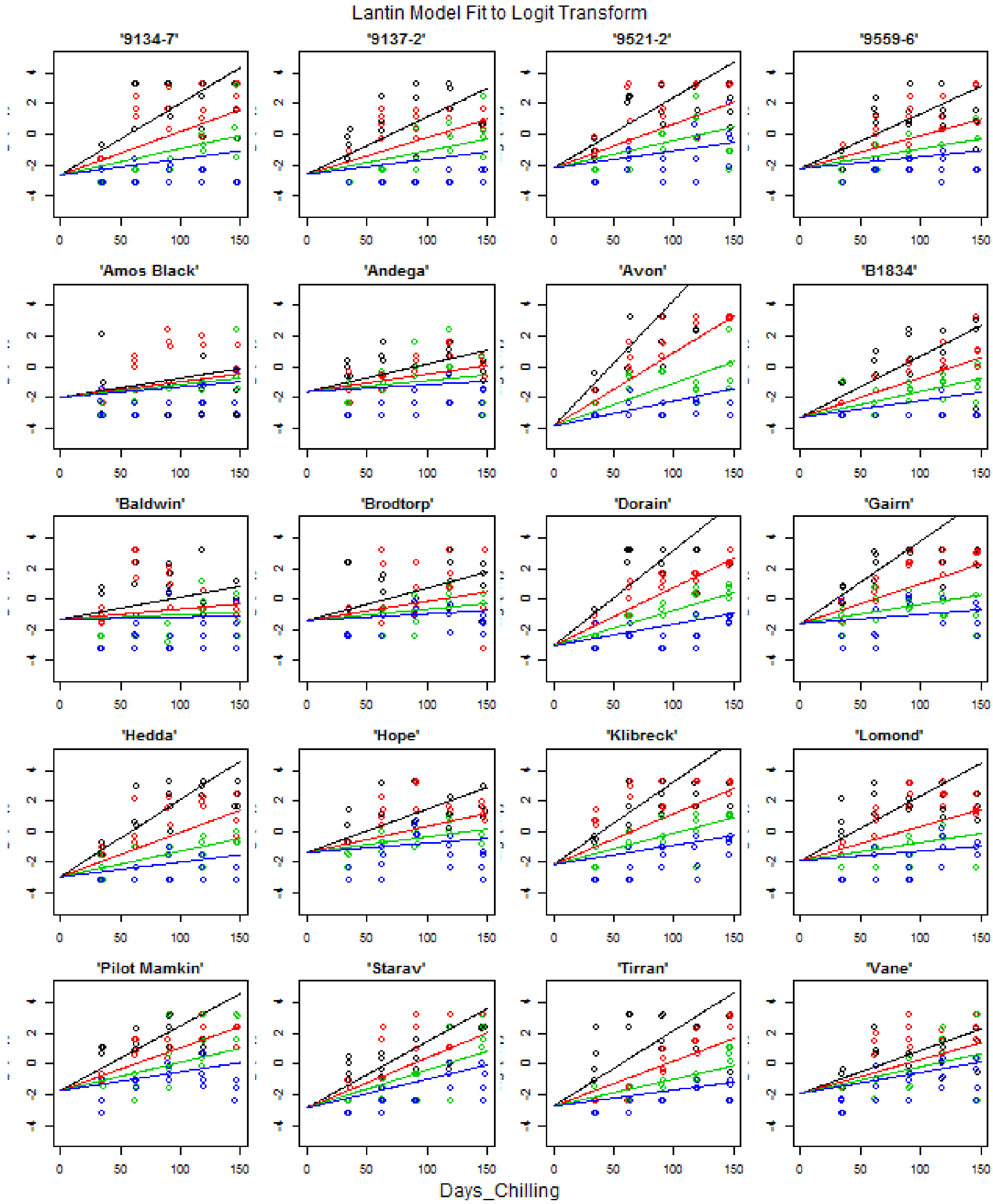


Figure S2 Logit transform of the proportion of buds broken at the end of the controlled data experiment. Lines represent predictions from the Lantin model and points represent observed data. Black shows outcomes at -5 °C, red 0 °C, green 5 °C and blue 10 °C.

S.2 Jones model:

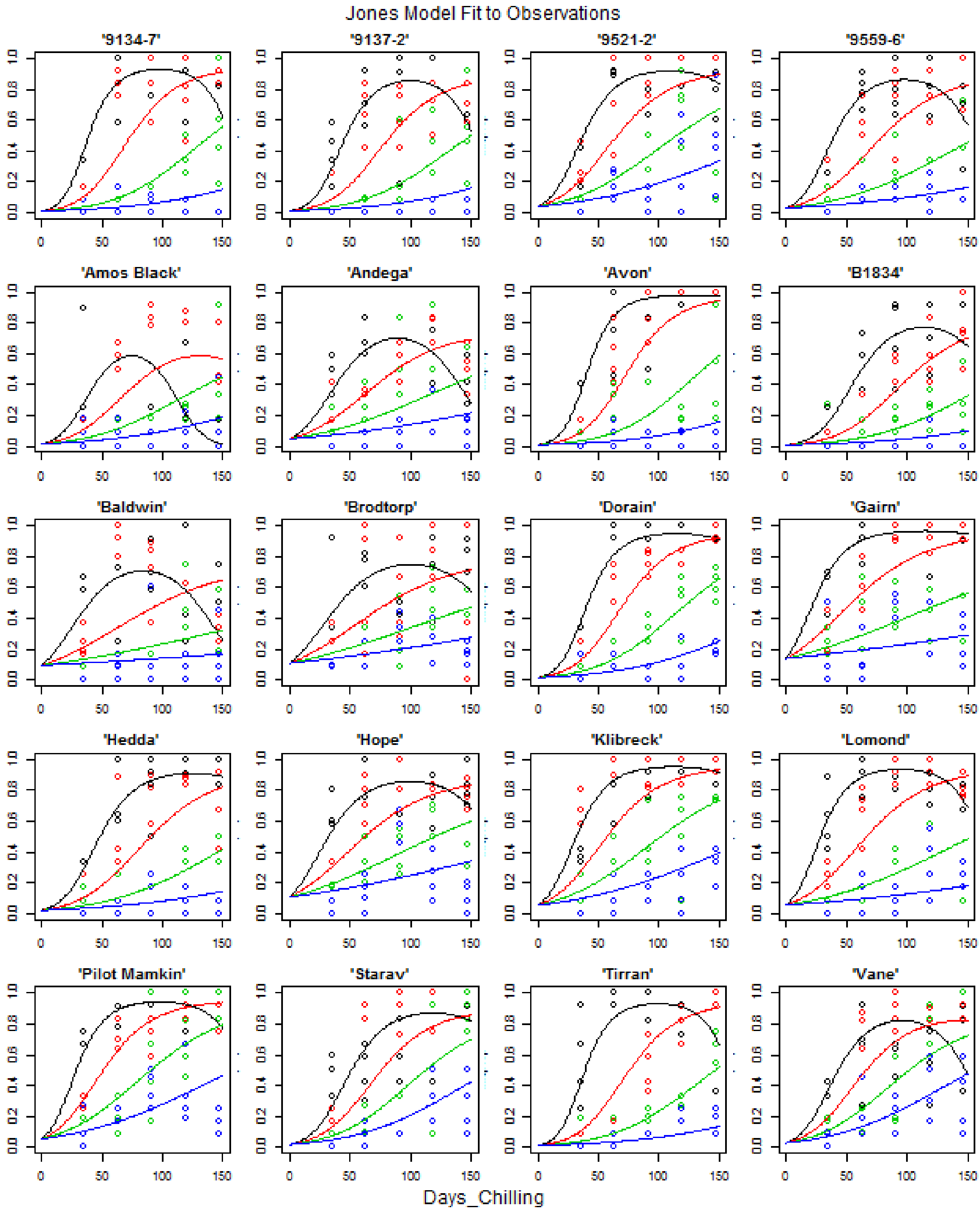


Figure S3 Proportion of buds broken at the end of the controlled data experiment. Lines represent predictions from the Jones model and points represent observed data. Black shows outcomes at -5 °C, red 0 °C, green 5 °C and blue 10 °C.

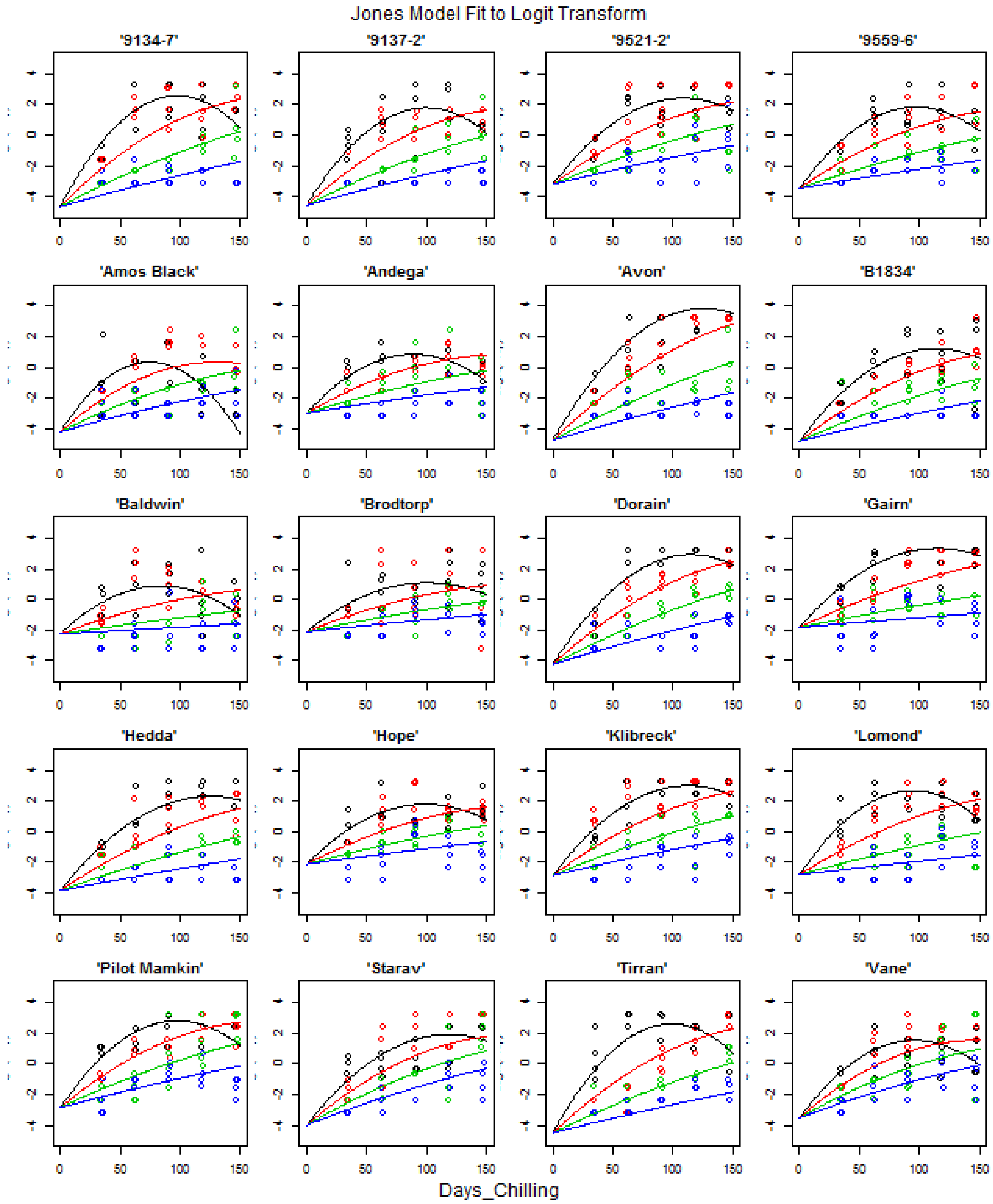


Figure S4 Logit transform of the proportion of buds broken at the end of the controlled data experiment. Lines represent predictions from the Lantin model and points represent observed data. Black shows outcomes at -5 ºC, red 0 ºC, green 5 ºC and blue 10 ºC.

S.3 Generalized Jones model:

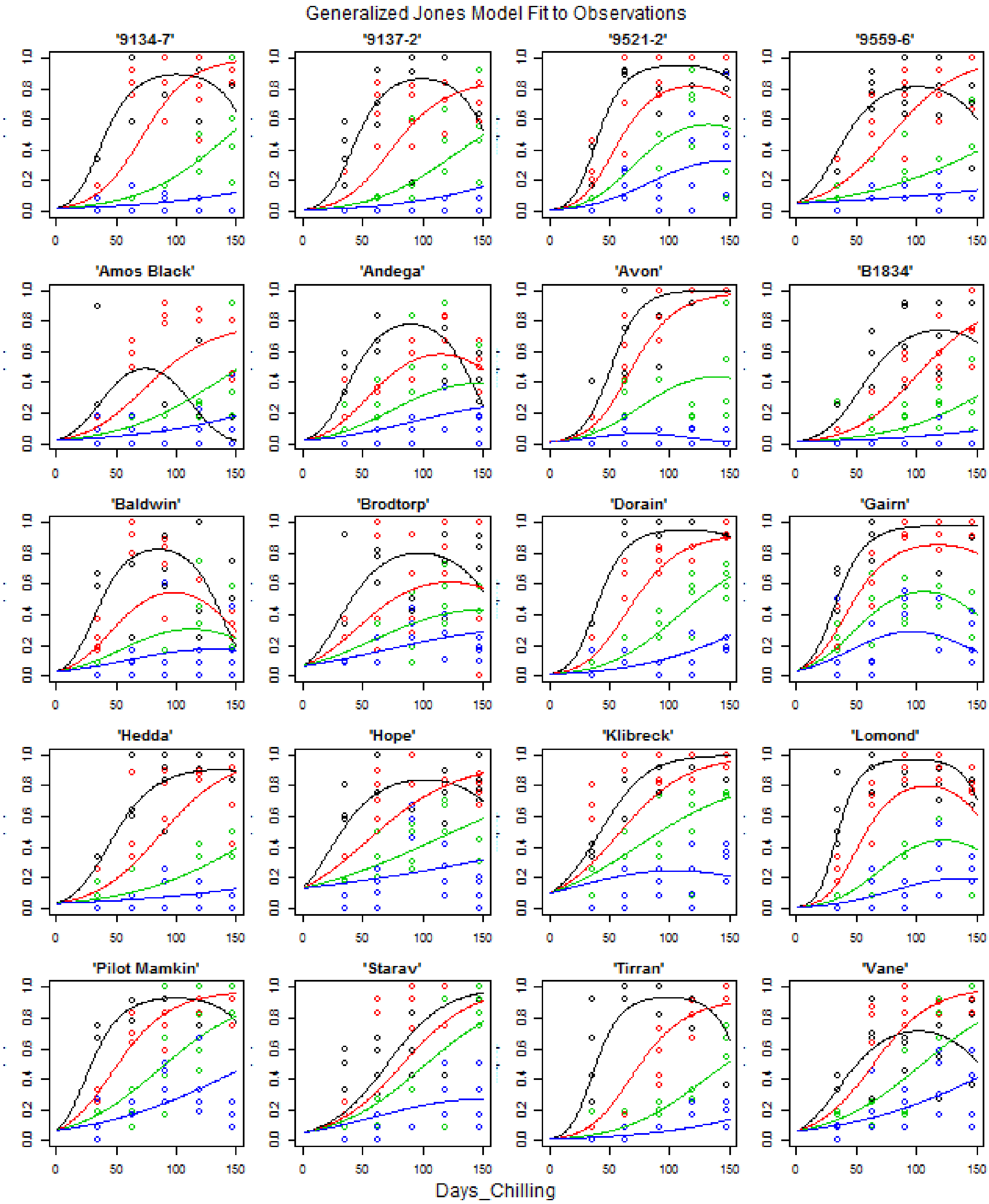


Figure S5 Proportion of buds broken at the end of the controlled data experiment. Lines represent predictions from the Generalized Jones model and points represent observed data. Black shows outcomes at -5 °C, red 0 °C, green 5 °C and blue 10 °C.

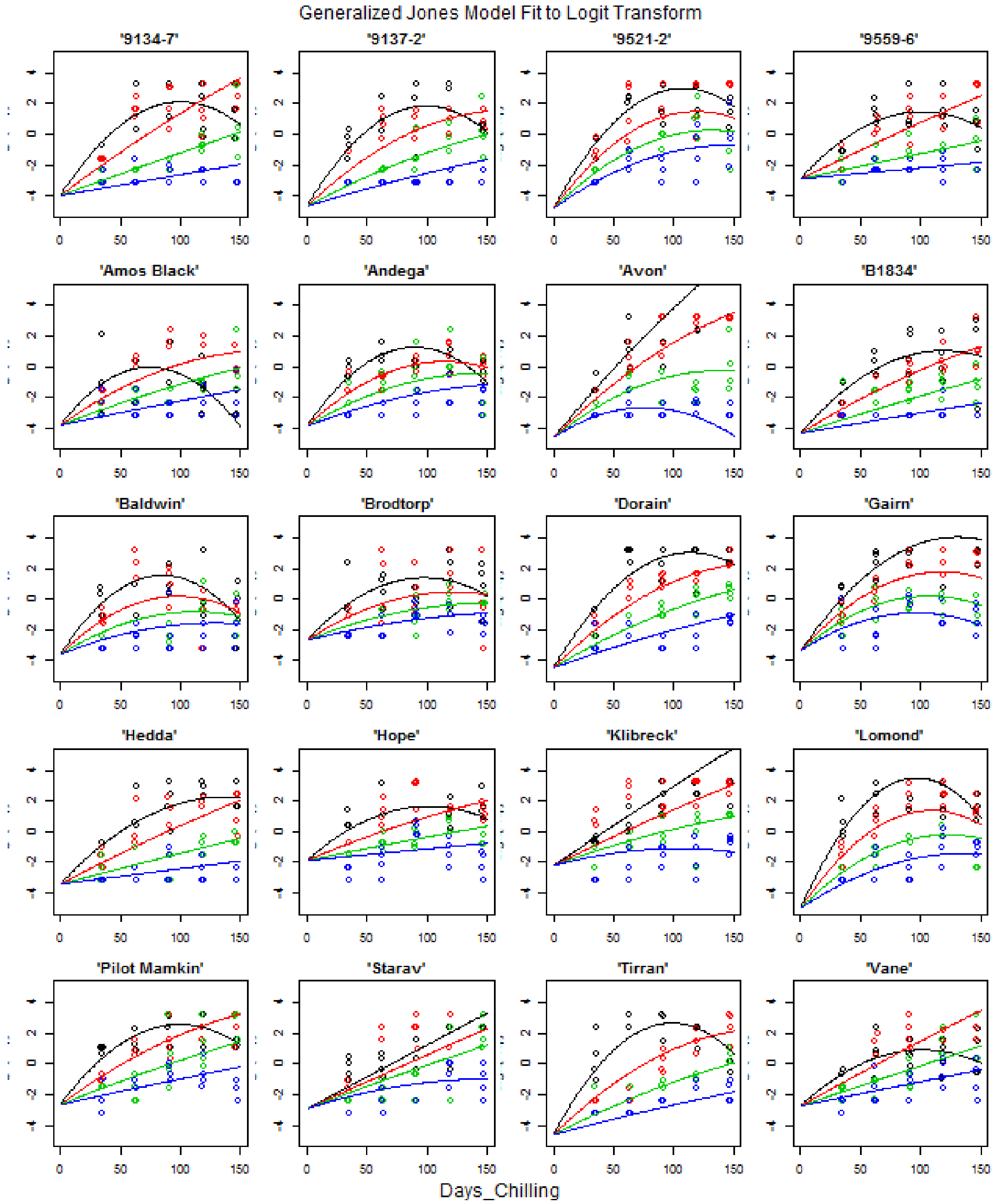


Figure S6 Logit of the proportion of buds broken at the end of the controlled data experiment. Lines represent predictions from the Generalized Jones model and points represent observed data. Black shows outcomes at -5 ^{o}C, red 0 ^{o}C, green 5 ^{o}C and blue 10 ^{o}C.