Grain yield response to sowing time, how many different response curves and maturity groups are there? Developing maturity type grain yield response curves to sowing time in Western Australia

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Abstract
Current agronomic recommendations for variety maturity descriptions are based on flowering response to sowing date rather than grain yield yet yield response to sowing date is what is most important to industry in making variety by sowing date decisions. Flowering and grain yield to sowing date response curves were compared for ~45 wheat varieties sown over 8 sowing dates from mid-April to mid-June from 2015-2018. Varieties were grouped using a novel statistical approach where statistical cluster analysis was implemented on spline coefficients of the response curves. Four distinct flowering date and grain yield responses to sowing date were developed. Flowering date clusters were robust and repeatable across site and season but did not always cluster varieties into the same group as grain yield response. The grain yield response curve clusters were not as consistent across seasons with swap over between quick and mid-season spring varieties but more consistent for longer season varieties (mid-slow spring to winters). Ultimately a varieties grain yield response to sowing date should be the basis for maturity type agronomic recommendations for industry rather than flowering date, but ongoing work is required to develop consistent approaches for variety grain yield response groupings.

Keywords frost, heat, modelling, varieties, time of sowing, flowering time

Introduction
In broad-acre cropping regions of Australia, frost risk is an important consideration for growers when implementing their cropping program. In Western Australia (WA), since the 1990s the average grower's cropping program has considerably increased in size. Sowing dates of wheat have shifted earlier, with a considerable proportion sown dry in most years to reduce heat and drought risk for the later part of the program. Conversely, while delaying sowing and/or using later maturing varieties has historically been the primary agronomic approach to reduce frost risk, this is no longer a viable option due to more variable season breaks and declining spring rainfall (Guthrie and Bowran 2021). Agronomic recommendations to industry about the optimal sowing date for a particular variety is the best way to manage frost risk but often based on its flowering date response to sowing date from paired rows or hill plots (FlowerPower 7 https://www.agric.wa.gov.au/flowerpower) or limited grain yield responses across sowing dates (Shackley et al. 2018). This approach, combined with the flowering date response, leads to phenology classifications and optimal sowing window recommendations of different varieties typically used in industry sowing guides such as Shackley et al. (2021) and Mathews et al. (2021). In addition, Australian Crop Breeders Ltd (2020) have developed their system to standardise nomenclature nationally across cereals. Yield by sowing datasets however, often exhibit complex grain yield response to sowing date patterns as demonstrated by Leske et al. (2017) that simple parametric models cannot explain. Other approaches use optimum flowering windows determined by simple parametric regression (Flohr et al. 2018). Therefore, there is a requirement to develop non-parametric regression models that do not make as strong assumptions on the shape of the response curves. Splines, which are piecewise polynomials, offer two significant benefits over traditional parametric models. They are not imposing shapes to the curve like simple regression but allow the observed data to suggest it and are relatively easy to fit. Hence the objective of this study was to model flowering and grain yield response curves of wheat varieties to sowing date with splines and then perform cluster analysis on these splines to determine if this is a more robust method for variety sowing date recommendations.

Methods
Trials
Randomised block design trials with eight-time of sowing (ToS) blocks were established at two frost-prone sites in Western Australia: (1) Aldersyde; 30 km east of Brookton (-32.38°, 117.32°) in 2015 and (2) Dale;

20 km south-west of Beverly (-32.20°, 116.75°) in 2016-2018. Both sites were located in a frost-prone part of the landscape; stubble was burnt prior to sowing. Supplementary irrigation of ~20-40 mm was used for the uniform establishment for the first 3-4 sowing dates before the season's break. After that, sowing dates were selected based on the historical equidistant thermal time from ~April 15 to June 20. Phenology in each plot was scored weekly (from Z45-70) according to Zadoks et al. (1974) and then used to estimate canopy heading (Z55) and flowering dates (Z65) of the varieties. Grain yield was estimated with a small-plot research header.

Trial design and statistical analysis
The trials were sown in ToS blocks (considered environments) with a row-column trial design with 12 ranges and two replicates of each variety in each ToS and were blocked in two directions for ~60-70 wheat varieties (Cullis and Smith 2015). A multi-environment trial (MET) analysis was performed on the raw yield data to remove natural and extraneous variation in the field (Gilmour et al. 1997). The yield was modelled with a linear mixed-effects model with 'ToS', 'variety' and their interaction as fixed effects. The residual was assumed to have an autoregressive AR1 x AR1 structure. Additional fixed and random effects were added into the model to consider the spatial variation as required. The predicted means of each combination of ToS and variety were then obtained for clustering. The 2016 yield data (due to severe frost damage) was log-transformed before the MET analysis to satisfy normality assumption on the model and back-transformed to the original scale before clustering. The MET analysis was performed with the 'asreml' R package (Butler et al. 2009).

The clustering analysis objective was to group flowering or grain yield response curves to sowing date with similar shapes. Firstly, a MET analysis was carried out on the yield data to remove spatial variation in the field; secondly, a quadratic penalised splines model was used to estimate yield and flowering response curves. The model was fitted with the 'nlme' R package (Pinheiro et al. 2021) by transforming the spline model into a linear mixed-effects model (Ng 2019). The spline was parameterised with a B-spline basis with two equidistant interior knots to ensure the regression coefficients were on the same scale and minimise the domination of coefficients with a larger scale. Finally, a k-means clustering algorithm, as implemented in R (R Core Team 2021), was used to group the coefficients of the response curves (and, by extension, the varieties). Different clustering sizes were tested (2 to 10 clusters), and the cluster size of 4 was deemed to be optimal based on the variance explained by the model.

Results and discussion

Clustering of flowering to sowing date response curves
There are 4 maturity groups presented in Figure 1 and Table 1 correspond approximately to '1/short/quick', '2/mid/medium', '3/mid-long/medium-slow and '4/winter/slow-very slow' varieties (Cluster -Shackley et al. (2021); phenology nomenclature - Australian Crop Breeders Ltd (2020)). These phenology groups are reasonably consistent with the classification used in national industry guides such as the WA and NSW DPI crop variety sowing guides (Shackley et al. 2021, Matthews et al. 2021). The grouping was also consistent across different years, with very few swap-over varieties between groups over sites and seasons for the flowering date (see Table 1). However, only four main flowering date response curves to sowing date despite a wide set of germplasm evaluated considerably less phenology groups than what both WA and NSW industry guides (9-11 groups) and Australian Crop Breeders (12 groups) currently use/recommend. This may mean that as an industry, we are over-classifying phenology types, at the risk of creating increased confusion for advisers and growers when selecting varieties for sowing windows.

Clustering of grain yield to sowing date response curves
The yield response curves were also clustered into four groups, and the results are shown in Table 1 and Figure 1. However, grain yield response to sowing date does not necessarily match the grouping on flowering/phenology response curves to sowing dates (Table 1). There is also considerable swap-over, particularly in the 'cluster 1/short/quick' and 'cluster 2/mid/medium' groups from year to year (see Table 1). On the other hand, cluster' 3/mid-long/medium-slow and cluster '4/ winter/slow-very slow' are more consistent with the same varieties together every year in both flowering and grain yield response curves to sowing date (Table 1). As expected, grain yield response to sowing date depends on a variety's grain yield

response to sowing date (and by extension, phenology) and the season in which the crops were grown. In particular, the grain yield response curves are similar for all varieties in 2015 and 2017, resulting in the somewhat arbitrary clustering in clusters 1, 2, and 3. In 2017 one could even argue that there was only 2-grain yield response to sowing date (both 2015 and 2017 were seasons characterised by low frost). Furthermore, there are not many differences between clusters 1 and 2 in most sites and seasons (Figure 1) and these clusters representing the quick and mid springs could also be combined. In contrast, the yield response curves in 2016 (severe frost) and 2018 (moderate frost) are rather distinct from 2015 and 2017, and thus the 4 clusters on yield and flowering are apparent and broadly match up with little swap-over between groups. Further work is ongoing across this and other datasets to determine the robustness of this approach.

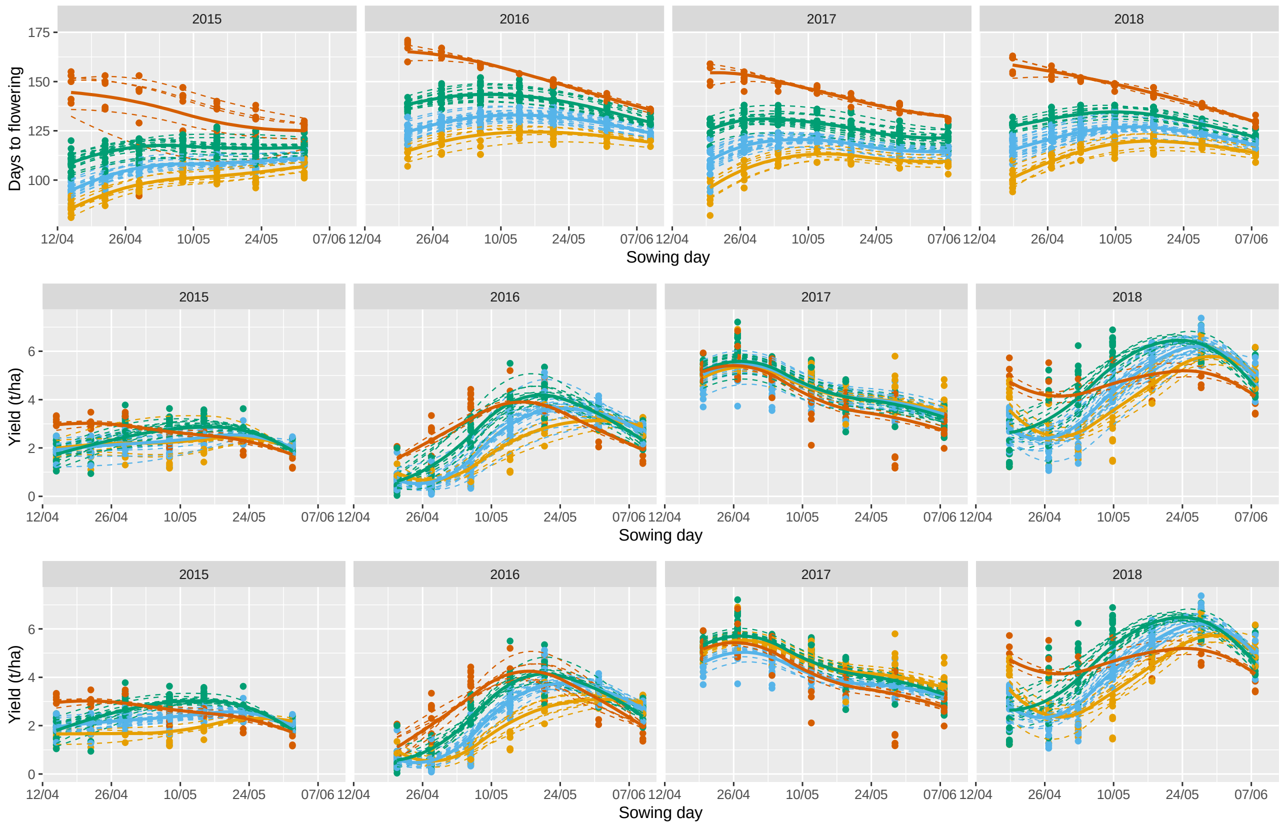

Figure 1. The flowering and grain yield response curves of 48 commercial wheat varieties at Aldersyde (2015) and Dale (2016-2018). The dotted lines are the yield/flowering response curves of each variety; the solid lines are the average of the cluster curves. The four clusters are coloured: yellow (1/short/quick); blue (2/mid/medium); green (3/mid-long/medium-slow); orange (4/winter/slow-very slow). The top row shows the flowering response curves (and flowering response clusters). The middle and bottom rows show the grain yield response curves, but the variety-specific curves are coloured by flowering and yield response clusters respectively. The solid points are either the observed days to flowering (top row) or the predicted grain yield means from the MET analysis (middle and bottom rows).

Conclusion

Clustering based on grain yield to sowing date response curves does not necessarily correspond to the clustering based on flowering to sowing date response curves. Furthermore, the grain yield clustering differs from year to year with fewer clusters in seasons with lower frost and higher terminal moisture stress. Variety maturity classifications based on yield response curves might be more informative than the traditional approaches based on phenology in the sense that it gives a more accurate description of the expected grain yield response for a variety enabling growers to select a variety for a sowing window. Ultimately a varieties grain yield response to sowing date should be the basis for maturity type agronomic recommendations for industry rather than flowering date. Work is ongoing to develop consistent approaches for variety grain yield response groupings.

Table 1. Clusters of selected varieties based on yield and flowering response curves from 2015 to 2018 arranged on days to flowering. Proposed phenology classification from Australian Crop Breeders Ltd (2020) also shown.

Variety	Phenology ACB	Yield				Flowering			
		2015	2016	2017	2018	2015	2016	2017	2018
Dart	Very Quick Spring	1	1	2	1	1	1	1	1
Condo	Quick Spring	1	1	2	1	1	1	1	1
Emu Rock	Quick Spring	2	1	1	1	1	1	1	1
Westonia	Quick Spring	2	2	1	1	1	1	1	1
Young	Quick Spring	2	1	1	1	1	1	1	1
Cosmick	Quick-Mid Spring	2	2	3	2	2	2	2	2
Crusader	Quick-Mid Spring	1	1	2	2	2	2	2	2
Hydra	Quick-Mid Spring	2	2	3	3	2	2	2	2
Impress CL Plus	Quick-Mid Spring	1	1	2	1	2	2	2	2
Suntop	Mid Spring	3	2	3	2	2	2	2	2
Mace	Mid Spring	2	1	2	2	2	2	2	2
Scepter	Mid Spring	NA	2	1	2	NA	2	2	2
Bremer	Mid-Slow Spring	3	3	1	3	3	3	3	3
Calingiri	Mid-Slow Spring	2	3	3	3	3	3	3	3
Kiora	Mid-Slow Spring	3	4	3	3	3	3	3	3
Lancer	Mid-Slow Spring	3	3	3	3	3	3	3	3
Magenta	Mid-Slow Spring	3	4	3	3	3	3	3	3
Yitpi	Mid-Slow Spring	3	3	2	3	3	3	3	3
Forrest	Very Slow Spring	4	4	4	4	4	4	4	4
EGA Wedgetail	Quick Winter	NA	4	4	4	3	4	4	4
Wylah	Mid Winter	4	4	4	4	4	4	4	4

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