SOWMAN: Sowing management for minimising the risk of frost and heat damage

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Abstract
Extreme temperature damage to Australian grain crops remains the major production constraint with estimated losses of $1,100M per year. Thus, it is crucial to reduce such losses to improve food security for Australian and international consumers. NSW DPI developed a computer based decision support called SOWMAN to help farmers select the most appropriate varieties at sowing for minimum risk of frost and heat damage. SOWMAN is based on a phenology model that integrates varietal response to vernalisation, temperature and photoperiod and their interactions. The phenological parameters of up to 163 varieties were fitted using multiple regression analysis, based on over 13,000 sowing-flowering observations. The parameterised variety models are established as site-specific models (SSMs) and generic models (GMs). GMs can be used when site specific field observations for a variety are unavailable. SOWMAN is currently applicable to southern NSW and can be applied to other regions when observed sowing-flowering data are available for model validation.

Keywords
Heat stress, wheat variety, barley variety, sowing decision, risk management, phenology.

Introduction
Extreme temperature damage from frost and heat stress are major production constraints in Australian grain crops with estimated annual economic losses is $1,100M (GRDC 2016). Frost damage is a major component of losses with cost of loss estimated to be $120 M to $700M annually (Crimp et al. 2016). Therefore, it is crucial for farmers to have a reliable risk management tool that can effectively reduce the risk of extreme temperature damage. In order to avoid both frost risk and heat stress, farmers have to ensure their crops flower in an optimum window during which both frost damage and heat stress risks are lowest. This can be a difficult and complicated decision-making process for farmers as sowing time varies and is largely dependent on the time of the seasonal break. NSW DPI developed the SOWMAN model, which incorporates variety phenology, combined with climate variability and climate conditions such as the Southern Oscillation Index (SOI) and risk of frost and heat stress at a specific location to help guide growers with their decision making regarding optimum sowing time and varietal choice for winter crops. The phenology model integrates temperature, photoperiod and vernalisation to predict the time of flowering of specific varieties (Liu 2007). Long term historical climate data is used to characterise the risk of frost and heat stress at flowering time so that varieties can be selected at sowing for minimum/acceptable risks of yield loss. The parameters that drive SOWMAN are derived from field observed sowing date and flowering date (denoted as sowing-flowering data), daily minimum and maximum temperature and geographical locations, using least-squared multiple regression. In this paper, we outline the behaviour of some newer varieties using the SOWMAN model.

Methods
Field experiment data
Phenology data of 167 wheat and 30 barley varieties from field trials across southern NSW have been used to validate SOWMAN model. These include phenology trails conducted by District Agronomists (PTDA) and national variety selection trails by breeders (NVTB). PTDA trials were conducted in 11 locations during 2002-2006, while NVTB experiments were run in 7 locations (Table 1). The total of 13,016 sowing-flowering observations were recorded, with a range of 1-3 replications.

Theory of the phenology model
The phenology model driving SOWMAN flowering prediction is described by Liu (2007). The model incorporates flowering responses to vernalisation, temperature and photoperiod to predict the time taken

from sowing to flowering. The effect of vernalisation on the time to flowering was modelled at the level of final leaf number. It was assumed that the number of final leaves is minimal for plants grown in temperatures conducive for vernalisation and maximal for plants grown in non-vernalising temperatures (Liu 2007). The daily progress of vernalisation is modelled by a combination of functions reported by Thornley and Johnson (1990) and Wang and Engel (1998).

Phenology parameters

The phenology parameters were fitted by least-squared multiple regression analysis, using sowing-flowering data and daily minimum and maximum temperature from sowing-date to flowering-date at the site. A computer program, called PhenoMod, was coded for determining the phenology parameters. Two types of models were developed, site-specific models (SSMs) and generic models (GMs). SSMs were developed when the observed sowing-flowering data of the variety were available for the site. GMs were developed with all available observations from all sites. The minimum data requirement for both GMs and SSMs is at least 5 sowing-flowering data as the model has 4 parameters to be fitted.

SOWMAN flowering window

The climate-risk based flowering window is used in SOWMAN (Liu et al. 2010). The optimum flowering window (D_{fw}) consists of day of the year (d_i) of suitable flowering. d_i is defined as when the probability of frost occurrences, $p_f(T_{mi}(d_i))$, is equal to or lower than the acceptable risk of frost damage (T_{cf}) and the probability of heat stress, $p_h(T_{mx}(d_i))$, is equal to or lower than the acceptable risk of heat stress (T_{ch}). Field experiments showed a reduction in relative grain yield of 5-7% per week when sowing was delayed after the end of June (Doyle and Marcellos 1974). Thus, fast-maturing varieties, sown later can flower within the optimum flowering window, but they must produce grain yield that is greater than an acceptable relative yield. The relative yield ($y_r(d_s,p)$) is a function of sowing date (d_s) and site-annual rainfall (p) (Doyle and Marcellos 1974; Perry et al. 1987). Therefore, the flowering window can be expressed as

$$D_{fW} = \left(\left(d_i \in D \mid p_f\left(T_{mi}(d_i)\right) \le T_{cf}\right) \le \alpha\right) \cap \left(\left(d_i \in D \mid p_h\left(T_{mx}(d_i)\right) \le T_{ch}\right) \le \beta\right) \cap \left(d_i \in D \mid y_r(d_s, p) \ge y_{rc}\right)$$

SOWMAN uses the following settings: T_{cf} = 2.0 °C, T_{ch} = 30 °C, α = 10%, β = 10% and y_{rc} = 0.65.

Table 1. Sowing-flowering observations recorded from field experiments conducted in southern NSW for current the update of SOWMAN. The values in brackets are the number of varieties being successfully parameterised.

Sites	Latitude	Longitude	Experiment year		No. of	No. of
			PTDA	NVTB	Varieties	observations
Albury			2003		11 (0)	53
Breeza	-31.242	151.423		2013	48 (39)	432
Condobolin	-36.069	146.953	2002-2005	2006,2008-2010,2012	71 (63)	1,105
Cowra	-33.802	148.704	2002-2006	2007-2011	75 (61)	2,451
Dareton	-34.107	141.919	2003-2006		38 (26)	447
Finley	-35.567	145.533	2002-2004		12 (7)	176
Griffith	-34.249	146.07	2002-2006		34 (33)	537
Hay	-34.5194	144.8545	2002		26 (0)	122
Narrabri	-29.8	149.5833		2013	24 (22)	208
Temora	-34.4061	147.5248	2002-2006	2006, 2008-2010	54 (51)	1,429
Trangie	-31.9861	147.9489		2008-2010	55 (55)	1,187
Wagga Wagga	-35.0517	147.3493	2002-2006	2008-2015	88 (73)	4,029
West Wyalong	-33.9387	147.0821	2002-2006		33 (33)	543
Yass	-34.8313	148.9113	2002-2004		20 (11)	297
Total					(465)	13,016
GM					197 (163)	

Results

Of the 193 varieties sown across the 14 years and 14 sites, 34 varieties had less than 5 sowing-flowering date observations. Therefore, only 143 wheat and 20 barley varieties were fitted by PhenoMod for GMs (Table 1). 465 SSMs were developed across the 12 sites. PhenMod was equipped with the *leave-k-cross validation* functions so the models can be independently validated with limited observed data. The results showed that the coefficient of determination (R^2) ranged between 0.6 and 1.0 with 95% of $R^2 > 0.8$ when the models are fitted and 85% of $R^2 > 0.8$ when models were cross-validated (Figure 1a). The root mean square error (RMSE) ranged from 0 to 12.5 days with the proportion of RMSE < 7.0 days being greater than 95% (601 out of 632) of the fitted cases and 94% when the models were cross-validated (Figure 1b). Cross-validation resulted in a slightly reduced R^2 and slightly increased RMSE from fitting. This indicates the robustness of phenology model and implies high accuracy of the models in predicting time to flowering.

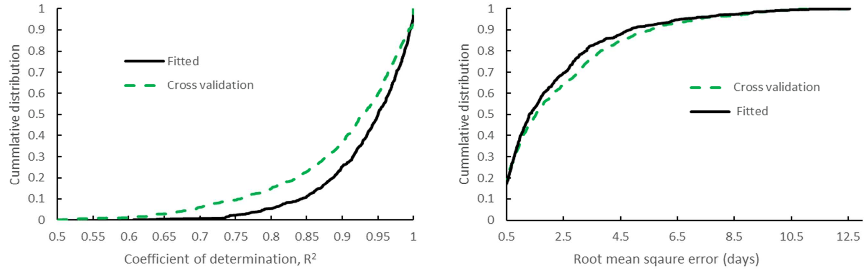

Figure 1. The cumulative distribution of the coefficient of determination (R^2) and root mean square error (RMSE) when fitting phenology model using multiple regression analysis and at leave-one-out cross validation in the combination of all NSW sites and varieties.

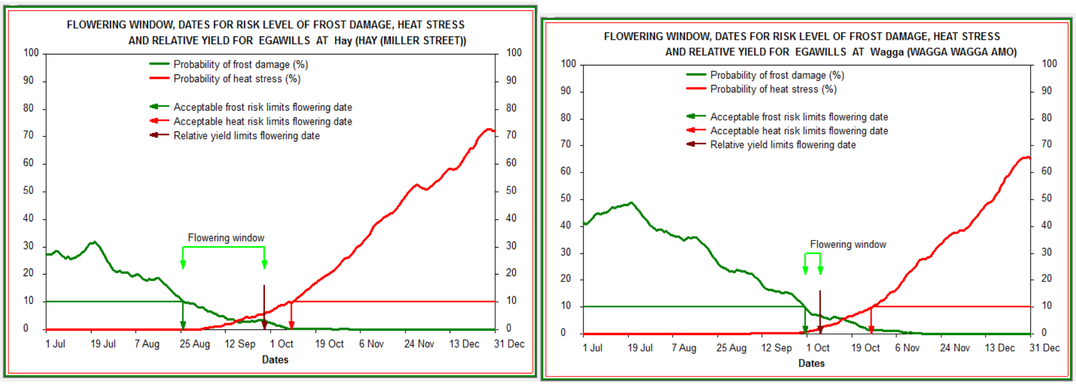

Figure 2. Risk of frost and heat stress and the flowering windows at Hay and Wagga Wagga, determined by extreme climate and acceptable crop yield projection (EGA Wills) for a sowing date (65% of relative yield).

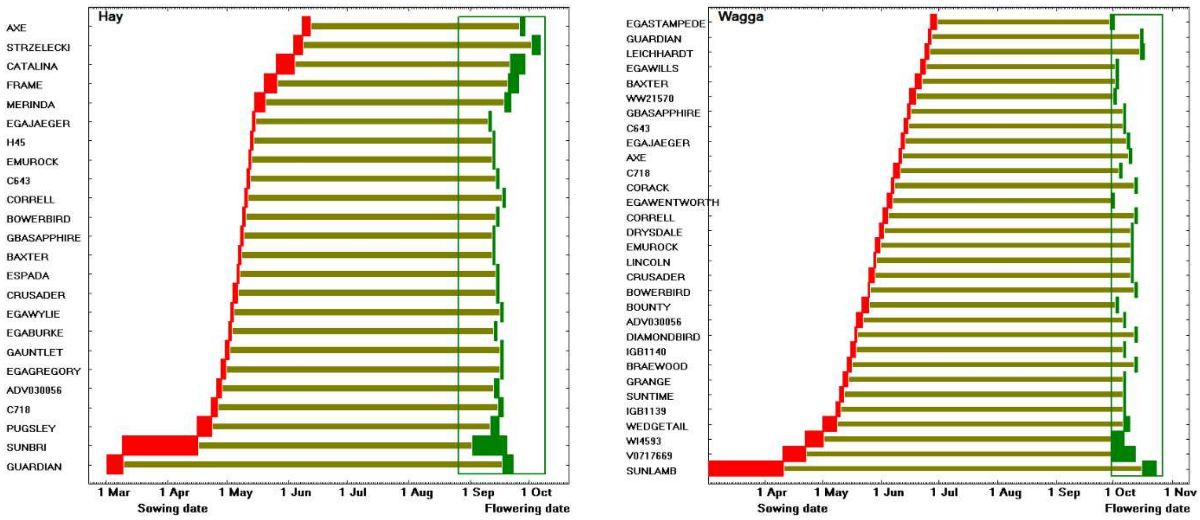

Figure 3. SOWMAN outputs of varieties selected for sowing at Hay and Wagga. The red bars are sowing dates and green bars are flowering dates with the green box indicating flowering widow with acceptable risk of frost and heat stress.

We used Hay (latitude: -34.5194, longitude: 144.8500) and Wagga Wagga (latitude: -35.0517, longitude: 147.340), as examples to demonstrate the SOWMAN recommendation of suitable wheat varieties to be sown at two contrasting sites. Flowering window at Hay is from 26 August to 8 Oct (Figure 2), however, crop yield can be lower than 65% relative yield when EGA Gregory is sown at a time which results in flowering occurring after 7th October. Flowering window at Wagga Wagga, is between 28 September and 26 October or no later than 21 October if less than 65% relative yield (EGA Gregory) sown is not acceptable (Figure 2). Because no SSMs were successfully established for Hay, GMs were used for all variety phenology predictions. A total of 23 varieties are recommended for Hay. They can be sown from 1 March to 11 June.

All of these varieties will flower between 2 September and 6 October at this relatively hot site. In contrast, at Wagga Wagga, a total of 37 varieties can be sown between 1 March and 27 June and the predicted flowering dates for these varieties are between 28 September and 22 October (Figure 3). The earliest variety able to be sown at Hay is Guardian, suitable from 1 to 7 March, flowering from 19 to 22 September. The earliest sowing variety sown for Wagga is Sunlamb, which can be sown from 1 March to 7 April for flowering between 16 to 22 October. It is interesting to note that both varieties respond to vernalisation, but the variety Sunlamb sown at Wagga Wagga has a much higher response (18.72 cumulative vernalisation days required) than variety Guardian sown at Hay (5.85 cumulative vernalisation days).

Discussion

Managing frost damage on wheat crops at flowering time differs from many other types of farm management such as weed and pest control and nutrient management. The problem is when the seeds are sown, the plant will develop towards flowering by intrinsic genes and environmental processes beyond the control of the farmer. Hence, the risk management for frost damage at sowing time is to select the right variety along with some paddock elevation considerations. There has been substantial research focus on breeding varieties with tolerance to frost and drought conditions, without any current commercial releases marketed as frost tolerant. Risk management strategies suggested for minimising the effects of frost and heat stress have and continue to included matching variety choice to sowing time. However, delaying sowing after the optimum is generally associated with a decrease in dry matter production and crop yields (Kerr et al. 1992). The most effective management strategy for growers is to ensure the most suitable variety is sown at time to ensure peak biomass accumulation and flowering occurs during the optimal window. An accurate prediction of time from sowing to flowering for a range of varieties provides a useful tool for growers and consultants to assist with the variety by sowing date decision making process. SOWMAN has been developed as a robust tool for variety choice in southern NSW. SOWMAN is generic enough to be applicable in other wheat growing areas. However, further work is needed to collate existing datasets or collect local variety sowing-flowering data to parameterise and/or validate the phenology models for the new areas.

Conclusion

With the collection of over 13,000 sowing-flowering observations from field trials conducted in southern NSW, we have determined phenology parameters for 143 wheat and 20 barley varieties in SOWMAN. The updated version of SOWMAN can help farmers and advisers make better decisions on selection of suitable varieties at sowing to minimise the risk of frost and heat damage reducing crop yield.

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