J1.16 EVALUATION OF FIVE THERMAL TIME MODELS FOR MODELLING SPRING WHEAT PHENOLOGICAL DEVELOPMENT ON THE CANADIAN PRAIRIES

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1. INTRODUCTION

Temperature is one of the most important environmental factors that regulate plant growth and development. Plants require a specific amount of heat or temperature units to develop from one stage to the other, such as from first-leaf to second-leaf stage or from seeding to maturity. Understanding and accurately predicting crop development stage (phenology) is fundamental to many aspects of crop production including optimising crop management practices such as fungicides, herbicides, pesticides and fertiliser applications and establishing more precise irrigation scheduling techniques (Gordon and Bootsma, 1993). In addition, precise prediction of crop phenological development is a vital requirement for crop simulation models, since models are increasingly being used as tools to assist with farm management decisions (Jame and Cutforth, 1997).

The thermal time concept is commonly used to assess crop development rate (CDR) as impacted by temperature (Gordon and Bootsma, 1993; Shaykewich, 1995; Saiyed et al., 2009). The thermal time concept takes into consideration the average daily air temperature (T_a) and the base temperature (T_b) for the crop in computing the number of heat units (HU) received during the day. Daily values are summed-up to give weekly, dekadal, monthly or seasonal totals. Consequently, this method can be more accurate than the calendar-day method for estimating crop phenology (Bauer et al., 1984; Russelle et al., 1984; Slafer and Savin, 1991) and subsequently timing of crop management strategies.

There are various thermal time models used to estimate crop phenological development, each with strengths and weaknesses (Shaykewich, 1995; Saiyed et al., 2009). The most frequently used thermal time models include the growing degree-days (GDD), which relates CDR linearly to temperature and the beta function (BF), which relates CDR to temperature nonlinearly. The objective of this study therefore was to compare and contrast five (5) different thermal time models for the purpose of identifying the best model for simulating spring wheat phenology in western Canada.

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2. MATERIALS AND METHODS

2.1 Experimental Location

Crop and weather data were collected from 2009 through 2011 from six field sites established across Manitoba (MB) and Saskatchewan (SK), providing a diverse range of contrasting growing conditions. In 2009, the sites used were Carman and Melita, MB, Regina, Melfort, Swift Current and Saskatoon, SK. In 2010 and 2011 the sites were Carman, Hamiota and Melita, MB, Regina, Melfort and Swift Current, SK. The sites are representative of the various soils and climatic conditions in western Canada.

2.2 Experimental design and data collection

Several spring wheat cultivars were grown at the six field sites during the 2009 through 2011 crop growing seasons. However for this study, crop growth and development (phenology) data for three widely-grown varieties namely AC Barrie, AC Intrepid and BW874 (Carberry) were utilised. These three varieties represent short, medium and long season varieties, respectively. The experimental layout at each site was a randomised complete block (RCD) design with four replicates (Fig. 1). Plot lengths ranged from 5 to 9 m, while row spacing ranged from 20 to 23 cm. The seeding rate was 275 seeds m^{-2} at all MB sites and 200 seeds m^{-2} at all SK sites. Fertilizer was applied according to soil test results at seeding time. Weeds and diseases were controlled using post emergence herbicides and pesticides, respectively.

At each site, phenological observations from emergence to vegetative phase were recorded weekly using the Haun scale (Haun, 1973). During the reproductive phase, observations were recorded using both the Haun scale and the Zadoks scale (Zadoks et al., 1974). Once heading began, the frequency of observations was increased in order to ensure that the initiation of anthesis was recorded. Following completion of anthesis, observations returned to weekly interval.

Daily weather data including minimum and maximum air temperature (T_a), dew point temperature, relative humidity (RH), solar radiation (R_s), precipitation and wind-speed were collected at each site from planting to harvest using on-site automated Davis Wireless Vantage Pro2 (Model 6152) weather stations. Details on the performance and siting of the weather stations are available in Ash and Wright (2011).

Figure 1: Plot experiments at different wheat growth stages and weather recording instruments.

2.3 Thermal Time Models Evaluated

Five thermal time models were tested for their ability to simulate spring wheat phenological development from planting (seeding) to maturity and they included the (i) NDGDD (developed in North Dakota) (NDAWN, 2012), (ii) GDD_0 (base temperature zero), (iii) GDD_5 (base temperature 5), (iv) Beta Function (BF) and (v) Modified Beta Function (MBF). Formulas for these models can be found in the following references; NDGDD (NDAWN, 2012); GDD_0 and GDD_5 (Gordon and Bootsma, 1993; Saiyed et al., 2009), BF (Jame et al., 1998; Wang et al., 2010) and MBF (Yan and Hunt, 1999; Yuan and Bland, 2005).

2.4 Data Analysis

The analysis involved correlating crop growth stage (phenology) for each variety at each site with accumulated GDD/daily growth rate (calculated using the five different thermal time models) from planting to anthesis. All sites within each year were combined and finally all years were combined to derive representative regression equations for each variety and the three varieties combined.

The ability of each model to predict time (calendar days) from planting to anthesis was tested using wheat phenology data collected in 2011 and data collected from five (5) experimental sites (i.e., Carman, Winnipeg, Melfort, Regina and Swift Current) from 2003 through 2006 giving a total of twenty (20) site-years of data. The overall predicted time (number of days) from seeding to anthesis was compared to the observed time using a student t-test at 5% probability level.

The performance of each model was evaluated using the root mean square error (RMSE), the mean absolute error (MAE), the mean bias error (MBE) all of which can be expressed in units of the observed data and the Willmott index of agreement (Wilmott, 1982; Willmott and Matsuura, 2005; Kahimba et al., 2009).

3. RESULTS AND DISCUSSION

3.1 Relationship Between Wheat Growth Stages and Accumulated GDD/Growth Rates

Figure 2 shows the linear relationship between wheat growth stage (planting to anthesis) for all cultivars, sites and years combined and accumulated GDD/daily growth rates calculated using the five different thermal time models. The relationship was highly significant with $p<0.01$ and R^2 ranging from 0.91 to 0.94, indicating that the developed models explained from 91% to 94% of the variability in wheat phenological development. All five models were equally good in explaining the variability as indicated by the almost similar R^2 values.

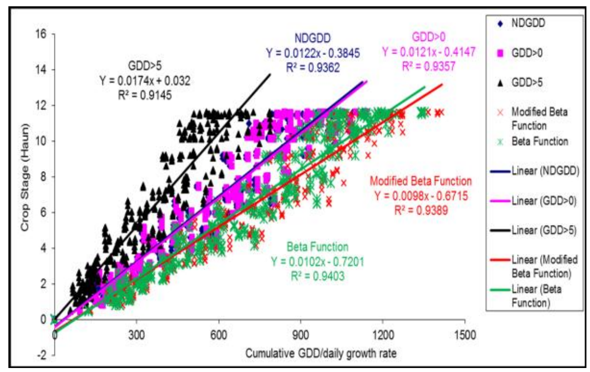

Figure 2: Linear relationship between wheat growth stage (planting to anthesis) and cumulative GDD/growth rate calculated using the five different models for all cultivars and years combined. Note; cumulative daily growth rate values for both the BF and MBF were multiplied by 100 so that they can be plotted on the same graph with the other models.

3.2 Models Testing

Figure 3 shows the linear relationship between predicted and observed time (calendar days) from planting to anthesis for cultivar AC Barrie. For all the models, the correlation is high with R^2 ranging from 0.77 to 0.83 and $p<0.01$, indicating that the models explained from 77% to 83% of the variability.

All the models except for the BF and MBF performed well in predicting the time from planting to anthesis for the cultivar AC Barrie. When averaged across all site-years, the predicted number of calendar days from planting to anthesis by the NDGDD, GDD_0, GDD_5, the BF and MBF models was 64, 64, 63, 65 and 65, respectively; while the observed number of calendar days was 60. Saiyed et al. (2009) analysed data collected from five wheat sites across western Canada and found that wheat cultivars grown on the Prairies including AC Barrie required on average 63 days to grow from planting to anthesis. A **Student's t-test** showed that the values (calendar days from planting to anthesis) predicted by the NDGDD, GDD_0 and GDD_5 were statistically similar ($p>0.05$) to the observed value. However, the values predicted by the

BF and MBF models were significantly higher ($p<0.05$) than the observed value. The root mean square error (RMSE) value for the NDGDD, GDD_0 and GDD_5 was 5 while that for the BF was 6 and that for the MBF was 7. The MAE values followed a similar trend as the RMSE values but were slightly lower, while the *d* values were >0.99 for all the models. Kirby and Weightman (1997) when studying discrepancies between observed and modelled wheat growth stages reported a root mean square difference (RMSD) of 8 days and an average difference of 5 days.

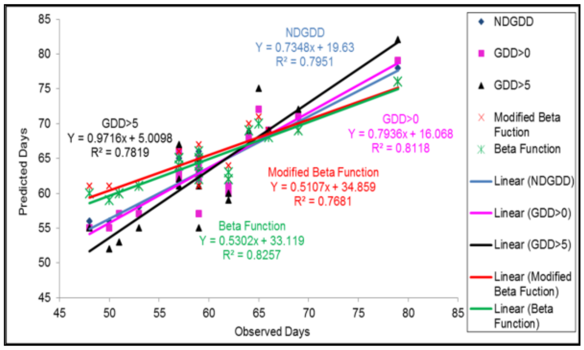

Figure 3: Linear relationship between predicted and observed time (calendar days) from planting to anthesis for all the thermal models.

4. CONCLUSIONS

Based on this analysis, the NDGDD, GDD_0 and GDD_5 models can be considered reliable predictive tools for estimating spring wheat phenological development in western Canada. WeatherFarm.com has adopted and deployed the NDGDD model for estimating spring wheat phenology across western Canada. This is a suitable choice; nonetheless, the model must be tested, validated and updated as new spring wheat varieties are released and the effects of climate change and or variability become apparent.

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REFERENCES

Ash, G. and Wright, H., 2011: Statistical comparison between WeatherFarm, Environment Canada and MAFRI weather stations at Carberry, MB, Canada.

Bauer, A., Frank, A.B. and Black, A.L., 1984: Estimation of spring wheat leaf growth rates and anthesis from air temperature. *Agron. J.,* 76, 829-835.

Gordon, R. and Bootsma, A., 1993: Analyses of growing degree-days for agriculture in Atlantic Canada. *Clim. Res.*, 3, 169-176.

Haun, J. R., 1973: Visual quantification of wheat development. *Agron. J*., 65, 116-119.

Jame, Y.W. and Cutforth, H.W., 1997: Crop growth models for decision support systems. *Can. J. Plant Sci.*, 76, 9-19.

Jame, Y.W., Cutforth, H.W. and Ritchie, J.T., 1998: Interaction of temperature and daylength on response leaf appearance rate in wheat and barley. *Agric. For. Meteorol.*, 92, 241-249.

Kahimba, F.C., Bullock, P.R., Sri-Ranjan, R., Cutforth, H.W., 2009: Evaluation of the SolarCalc model for simulating hourly and daily incoming solar radiation in the Northern Great Plains of Canada. *Can. Biosyst. Eng.*, 51, 1.11-1.21.

Kirby, E.J.M. and Weightman, R.M., 1997: Discrepancies between observed and predicted growth stages in wheat. *J. Agric. Sci.*, 129, 379-384.

NDAWN, 2012: Wheat growth stage prediction using growing degree days (GDD). (Accessed June 2012). http://ndawn.ndsu.nodak.edu/help-wheat-growing-degree-days.html

Russelle, M.P., Wilhelm, W.W., Olson, R.A. and Power, J.F., 1984: Growth analysis based on degree days. *Crop Sci.*, 24, 28-32.

Saiyed, I.M., Bullock, P. R., Sapirstein, H.D., Finlay, G.J. and Jarvis, C.K., 2009: Thermal time models for estimating wheat phonological development and weather-based relationships to wheat quality. *Can. J. Plant Sci.*, 89, 429-439.

Shaykewich, C.F. 1995: An appraisal of cereal crop phenology modelling. *Can. J. Plant Sci.*, 75, 329-341.

Slafer, G.A. and Savin, R. 1991: Developmental base temperature in different phenological phases of wheat (*Triticum aestavum*). *J. Exp. Bot.*, 42, 1077-1082.

Wang, H., Cutforth, H., DePauw, R.M., McCaig, T., McLeod, G., Brandt, K., and Qin, X. 2010: Modelling leaf appearance rate for Canada Western red spring wheat cultivars. *Can. J. Plant Sci.*, 90, 399-402.

Willmott, C.J., 1982: Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc.*, 63, 1309-1313.

Willmott, C.J., Matsuura, K., 2005: Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. *Clim. Res.,* 30, 79-82.

Yan, W. and Hunt, L.A., 1999: An equation for modelling the temperature response of plants using only the cardinal temperatures. *Ann. Bot.*, 84, 607-614.

Yuan, F.M. and Bland, W.L., 2005: Comparison of light- and temperature-based index modelsfor potato (Solanum tuberosum L.) growth and development. *Am. J. Potato Res.*, 82, 345-352.

Zadoks, J.C., Chang, T.T. and Konzak, C.F., 1974: A decimal code for growth stage of cereal. *Weed Res.*, 14, 415-421.