Testing a nonlinear model for simulating the time of seedling emergence of wheat

H. Wang[1,2*], H. Cutforth[1], P.R. Bullock[3], R.M. DePauw[1], T. McCaig[1], G. McLeod[1], K. Brandt[1] and G.J. Finlay[4]

*[1]Semiarid Prairie Agricultural Research Centre, Agriculture and Agri–Food Canada, Box 1030, Swift Current, Saskatchewan, S9H 3X2 Canada; [3]Department of Soil Science, University of Manitoba, 362 Ellis Building, Winnipeg, Manitoba, R3T 2N2 Canada; and [4]The Canadian Wheat Board, 423 Main Street, P.O. Box 816, Stn. Main, Winnipeg, Manitoba, R3C 2P5 Canada. *Email: hong.wang@agr.gc.ca*

Wang, H., H. Cutforth, P.R. Bullock, R.M. DePauw, T. McCaig, G. McLeod, K. Brandt and G.J. Finlay. 2009. **Testing a nonlinear model for simulating the time of seedling emergence of wheat.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada. 51: 4.1–4.6. Previous research found that a model that used a series of Beta functions (Beta model) was better than linear models for simulating the days from seeding to seedling emergence (DSE) of wheat (*Triticum aestivum* L.). To further validate the Beta model we used three sets of field studies conducted in North America: (1) a seeding date study at Moro, OR (38 seeding dates); (2) a multi-year, multi-site study in Canada (98 site-years); and (3) a series of experiments at Swift Current, SK (20 treatment-years). Results demonstrated that the linear emergence module in the Cropping System Model of The Decision Support System for Agrotechnology Transfer (DSSAT–CSM) tended to underestimate DSE. The Beta model using either daily or hourly air temperature markedly improved the simulation of DSE for all three studies. The Beta model using simulated soil temperature slightly improved simulation, but was not as good as that using air temperature, which was caused by the inaccuracy of soil temperature simulation. It seems that the Beta model is an appropriate model to predict seedling emergence of wheat grown in North America. There were no significant differences in DSE among wheat genotypes used in studies at Moro or Swift Current. **Keywords:** seedling emergence, modelling, Beta function, wheat.

Des recherches antérieures ont démontré qu'un modèle qui utilise une série de fonctions Beta (modèle Beta) était meilleur que les modèles linéaires pour simuler le nombre de jours écoulés entre le semis et l'émergence des plants (JEP) de blé (*Triticum aestivum* L.). Dans le but de valider ce modèle sous différentes conditions, nous avons utilisé des données provenant de trois séries d'études au champ réalisées en Amérique du Nord: (1) une étude de semis à Moro, OR (38 dates de semis); (2) une étude réalisée sur plusieurs années et plusieurs sites au Canada (98 sites-ans); et (3) une série d'expériences réalisées à Swift Current, SK (20 traitements-ans). Les résultats ont démontré que le module d'émergence linéraire du modèle « Cropping System Model » du système « Decision Support System for Agrotechnology Transfer » (DSSAT–CSM) avait tendance à sous-estimer JEP. Le modèle Beta faisant appel aux températures de l'air journalières ou horaires a amélioré de manière remarquable la simulation des JEP pour les trois études. Le modèle Beta qui utilisait les températures de sol simulées améliorait légèrement la simulation mais n'était pas aussi bon que si la température de l'air était utilisée et ceci était dû à l'imprécision de la simulation de température de sol. Il semble que le modèle Beta soit un modèle approprié pour prédire l'émergence des plants de blé cultivés en Amérique du Nord. Il n'y avait pas de différences significatives dans les JEP entre les génotypes de blé utilisés dans les études réalisées à Moro et à Swift Current. **Mots clés:** émergence des plants, modélisation, fonction Beta, blé.

INTRODUCTION

The uniformity and rapidity of seedling emergence of wheat (*Triticum aestivum* L.) influences the success of the grain and biomass production (Gan et al. 1992; Forcella et al. 2000), especially when grown under suboptimum conditions, such as a short growing season and/or heavy weed competition. The accuracy of seedling emergence prediction is important for crop management practices such as control of weeds, disease and insects and for predicting phenological development and yield, especially for farmers who manage large areas of land to arrange field operations. The accuracy of emergence prediction is also crucial for the performance of growth models.

Many phenological models, such as CERES (Ritchie and Otter 1985), APSIM (Keating et al. 2003) and DéciBlé (Chatelin et al. 2005), assume that the rate of seedling emergence is linearly related to temperature. Recent studies, however, found that the response curve of plant development rate to temperature is nonlinear (Shaykewich 1995; Forcella et al. 2000). Jame and Cutforth (2004) separated the period between seeding and emergence of wheat into three consecutive processes (germination, subcrown internode elongation if seeding depth is deeper than 25 mm, and coleoptile elongation) and used a series of beta functions (Beta model) to describe the effect of temperature on development rates of these processes. The Beta model simulated the time of seedling emergence satisfactorily under both controlled environments and field conditions (Jame and Cutforth 2004).

Wang et al. (2009) slightly modified the parameters of the Beta model for wheat cultivars grown in North America and incorporated the Beta model into the Decision Support System for Agrotechnology Transfer–Cropping System Model (DSSAT–CSM). The modified model was tested using observations of spring wheat (cv. Thatcher) from 24 sites across North America from 1930 to 1954 (Nuttonson 1955). The simulation of seedling emergence performed well with high precision [Pearson's correlation (r) was 0.66, $P < 0.001$] and high accuracy (root mean square errors (RMSE) was 3.1 days]. The objective of this study was to use more observed data to further validate the Beta model for simulating the timing of seedling emergence of wheat grown in North America.

MATERIALS and METHODS

The Beta model

Jame and Cutforth (2004) used the following Beta function to simulate the daily rates of germination (day^{-1}) and coleoptile elongation (mm day^{-1}):

$$\text{Rate} = \text{EXP}(\mu) \times (T - T_b)^{\alpha} \times (T_c - T)^{\beta} \quad (1)$$

where T is temperature in °C ($T_b < T < T_c$), T_b and T_c are base and upper critical temperatures, respectively, μ, α and β are the model parameters.

They used the following equation to simulate the rate of subcrown internode elongation (mm day^{-1}):

$$\text{Rate} = A - B \times (D - 25) \quad (2)$$

Where

$$\text{A} = \text{EXP}(\mu 1) \times (T - T_b)^{\alpha} \times (T_c - T)^{\beta} \quad (3)$$

$$\text{B} = \text{EXP}(\mu 2) \times (T - T_b)^{\alpha} \times (T_c - T)^{\beta} \quad (4)$$

and D is the seeding depth (mm).

All parameters in this study were derived using only Canadian cultivars from a study previously reported by Wang et al. (2009) and are listed in Table 1. The Beta model was incorporated into DSSAT–CSM and was run by the sequence mode.

Table 1. Parameters of Beta model adopted from Wang et al. (2009).

T_b	1°C
T_c	39°C
Germination	
μ	−4.63
α	1.27
β	0.119
Coleoptile elongation	
μ	−1.0164
α	0.8207
β	0.26
Subcrown internode elongation	
$\mu 1$	−2.8681
$\mu 2$	−7.8401
α	1.6
β	0.697

Model validation

Moro sudy A seeding date study was initiated in Moro, OR (Table 2). It used 40 seeding dates that ranged from February 2, 1924 to July 6, 1927, with a seeding date separation of ten days to one month. Among them were 38 seeding dates with emergence records. A total of 22 varieties were used over the duration of this study. There were 11 winter wheat varieties (Kharkov, Oro, Regal, Kanred, Blackhull, Turkey, Ridit, Triplet, White Odessa, Fortyfold and Hybrid 128), four intermediate (Hybrid 63, Hybrid 143, Federation and Pacific Bluestam), six hard red spring wheat varieties (Jenkin, Galgalos 39, Marquis, Hard Federation, Quality, Sunset) and one hard white spring wheat (Baart). Details of this study were reported by Bayles and Martin (1931).

Multi–year, multi–site study Marquis wheat was grown at nine sites in four provinces and one territory in Canada from 1953 to 1962 (Table 2). All plots were fertilized to achieve optimum production based on the soil type at each location. Dates of emergence were recorded in 98 site–years. The details of this study are described by Robertson (1968).

SPARC studies Several studies were conducted on a Swinton loam soil (Orthic Brown Chernozem) at the Semiarid Prairie Agricultural Research Centre (SPARC) near Swift Current, Saskatchewan (Table 2). The first study was a water stress experiment conducted in 1989, 1990, 1992, 1993, 1994, and 1995 with three water treatments (no irrigation, irrigation before seeding and irrigations during the growing season to keep soil water in the root zone above 60% of the potential plant extractable water). Two CWRS cultivars, Neepawa and Katepwa were seeded from 1989 to 1990 and from 1992 to 1995, separately. More details of the experiment were given by Jame et al. (1998).

The second study was a seeding date experiment conducted in 1989 and 1990. Neepawa and a semidwarf, high-yielding Canada Prairie Spring (CPS) wheat, HY 320, were seeded on four seeding dates from April to June each year on summerfallow under dryland conditions. A split–plot design was used with dates as main plots and cultivars as sub-plots. There were four replicates for each seeding date. More information of this study was described by Jame and Cutforth (2004).

The third was a physiology study conducted from 1998 to 2001, designed to compare physiological characteristics among some old and recently released spring wheat and durum (*Triticum turgidum* L. var *durum*) cultivars. Six CWRS cultivars (AC Barrie, AC Cadillac, AC Elsa, AC Intrepid, Neepawa and Marquis), four Canada Western Amber Durum (CWAD) wheat cultivars (AC Avonlea, AC Navigator, Kyle and Hercules) and a durum advanced line, DT 618 were grown from 1998 to 1999. In 2000, a CWRS cultivar, Superb, and a CWRS advanced line, BW 245, were added to the test. In 2001, six CWRS cultivars (Superb, AC Barrie, AC Elsa, Grandin, Neepawa and Marquis) and nine CWRS advanced lines (BW 245, BW 754, BW 755, BW 766, BW 768, BW 770, BW 771, UM 632 and UM 684) were seeded. Plants were grown on summerfallow with four replications using a randomized

Table 2. Information of sites.

Site	Province/ State	Latitude (°N)	Longitude (°E)	Elevation (m)	Soil zone	Study
Moro	OR	45.5	120.7	570	Brown	Moro Study
Fort Simpson	NW	61.9	121.4	169	Grey	Multi-Year Multi-Site study
Fort Vermillion	AB	58.4	116.1	278	Grey	Multi-Year Multi-Site study
Beaverlodge	AB	55.2	119.4	732	Grey	Multi-Year Multi-Site study
Lacombe	AB	50.5	113.8	848	Black	Multi-Year Multi Site study
Kapuskasing	ON	49.4	82.4	224	Grey	Multi-Year Multi-Site study
Normandin	ON	48.9	72.5	137	Brown	Multi-Year Multi-Site study
Ottawa	ON	45.4	75.7	79	Grey	Multi-Year Multi-Site study
Harrow	ON	42.0	82.9	191	Grey	Multi-Year Multi-Site study
Swift Current	SK	50.4	107.9	825	Brown	Multi-Year Multi-Site study, SPARC Studies

complete block design. Specific details of this study have been previously reported by Wang et al. (2002, 2007).

Finally, we included a study conducted from 2003 to 2006 examining the effects of genotype and environment on wheat end-use suitability. Four CWRS cultivars (Superb, AC Barrie, AC Elsa and Neepawa), one CPS–white cultivar, AC Vista, and a Canadian Western Hard White Spring (CWHWS) cultivar, Snowbird, were grown on summerfallow with three replications using a randomized complete block design. Details of this study have been previously reported by Finlay et al. (2007).

For all experiments conducted at SPARC the seeding depths were 3–5 cm. After seeding, the plots were observed at least every 2–3 days and emerging plants were counted from a 1-m row located in the center of each plot to determine the date of emergence, which was defined to occur when the tip of the first leaf emerges from the soil surface for 50% of the plant population. For the Moro Study and Multi–Year, Multi–Site Study, we assume that (1) the seedling emergence was defined using the same definition as the SPARC Studies; (2) the management was fallow–wheat rotation under conventional tillage; and (3) the seeding depth was 5 cm.

The DSSAT–CSM requires weather data and soil physical and chemical properties at each site. Daily maximum and minimum air temperatures and precipitation were downloaded from United States Historical Climatic Network (National Climatic Data Centre 2008) and the Agriculture and Agri–Food Canada (AAFC) Daily Climate Information website (Agriculture and Agri–Food Canada 2006). Daily solar radiations was calculated using the Mountain Climate Simulator (Thornton et al. 2000). The hourly air temperature was calculated using the subroutine HTEMP of DSSAT–CSM (Parton and Logan 1981). The soil properties (organic carbon, total nitrogen, clay and silt in percent, cation exchange capacity, pH, soil lower, drained upper and saturated points, saturated hydraulic conductivity, and bulk density) were downloaded from the United States Department of Agriculture Natural Resources Conservation Service soil survey characterization data website (United States Department of Agriculture–Natural Resources Conservation Service 2008) and AAFC Soil Landscapes of Canada website (Agriculture and Agri–Food Canada 2007).

Simulated and measured results were compared for consistent error, association and coincidence by mean difference (M, Addiscott and Whitmore 1987), Pearson's correlation (*r*, Draper and Smith 1966), and root mean square errors (RMSE, Loague and Green 1991), respectively.

RESULTS and DISCUSSION

Moro study

Because within a given seeding date the cultivar difference in days from seeding to seedling emergence (DSE) was very small (± 2 days. Bayles and Martin 1931), only means of DSE over all cultivars were used to compare with simulation results.

The broad range of seeding dates of this study (spring to winter) allowed seeds to experience a wide range of temperature and moisture, which resulted in DSE ranging from 5 to 59 days (Fig. 1). The longest DSE (59 days) was observed from the seeding date of December 12 1925. The high correlation coefficient between measured and simulated DSE by the original DSSAT-CSM model ($r = 0.82$, $P < 0.0001$, $n = 38$, Table 3) indicates that the structure of the model is probably correct (Smith et al. 1996), but the model underestimated DSE in most cases. The Beta model using hourly or daily air temperature markedly improved the simulation performance (with M closer to zero, lower RMSE and higher *r*) compared with the original model. The Beta model using simulated daily soil temperature slightly improved simulation, but was not as good as using air temperatures (Table 3), which could be caused by the inaccurate simulation of soil temperature at seeding depth by DSSAT-CSM (Wang et al. 2009).

Multi–year, multi–site study

Similar to the Moro Study, the original DSSAT-CSM model also tended to underestimate DSE of Marquis wheat. The Beta model simulated DSE very well in most cases using either daily or hourly air temperature (Table 3,

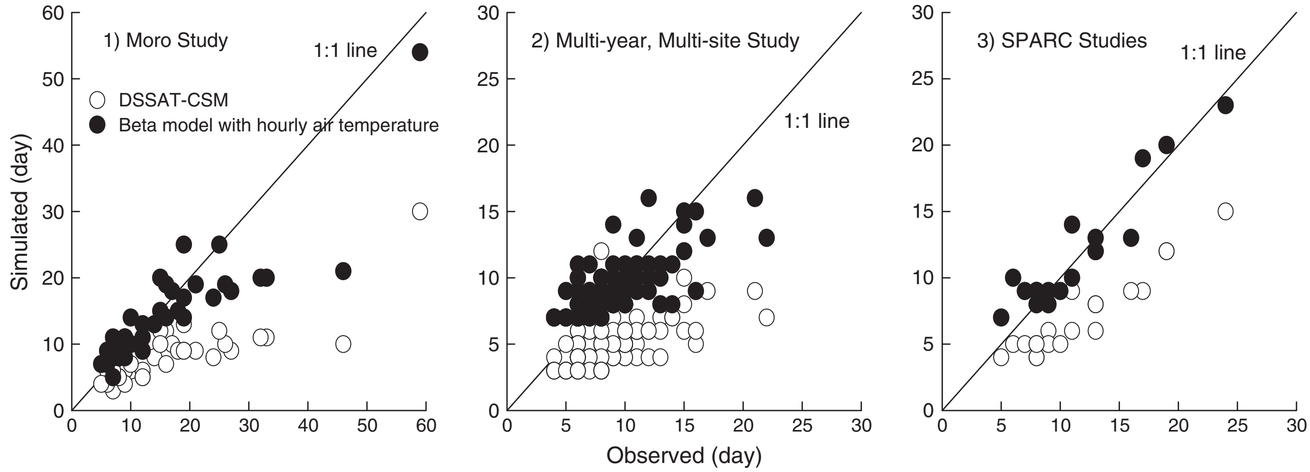

Fig. 1. Observed vs. simulated days from seeding to seedling emergence of spring wheat. (1) More Study, (2) Multi-year, Multi-site Study and (3) SPARC Studies.

Fig. 1). Again, the Beta model using simulated soil temperature only slightly improved the simulation.

SPARC studies

Similar to the Moro Study, there were no statistical differences in DSE between water treatments in any year of the water stress experiment or between Neepawa and HY 320 in either 1989 or 1990 of the seeding date study (Jame and Cutforth 2004). Over the 4-year physiology study and 4-year quality study, all genotypes in different wheat classes including CWRS, CWAD, CPS–white and CWHWS averaged the same DSE within a year with the standard errors being <1 day. Validation analyses were done, therefore, based on means of all genotypes or water treatments (Table 3, Fig. 1).

Similar to the Moro and Multi-year, Multi-site studies, the original DSSAT-CSM model underestimated DSEs. The Beta model using either daily or hourly air temperature improved simulation of DSE in terms of M and RMSE, but *r* was not increased. The Beta model using simulated soil temperature only slightly improved the prediction of DSE by reducing M and RMSE, but *r* was also reduced.

For all three studies, simulation performances of the Beta model with consideration of the water stress effect were very similar to that without consideration of the water stress effect (data not shown), which was probably because wheat can germinate under relatively dry conditions (Owen 1952; Lafond and Fowler 1989) and/or the inaccurate simulation of soil moisture at seeding depth by DSSAT-CSM (Wang et al. 2009). All above-mentioned results are consistent with results conducted by Wang et al. (2009).

In conclusion, results of this report are consistent with those reported by Jame and Cutforth (2004) and Wang et al. (2009), i.e., the Beta model substantially improved the simulation of seedling emergence of wheat. It seems that the Beta model is an appropriate model to predict seedling emergence of wheat grown in North America. If DSSAT–CSM uses the Beta function for simulating wheat seedling emergence it may result in more accurate predictions of phenology, biomass production and grain yield. Further work should be done to conduct survival analysis and dynamic modeling to describe the relationship between environment and the progress of seedling

Table 3. Mean difference (M), Pearson's correlation (*r*), and root mean square error (RMSE) between simulated and measured days from seeding to seedling emergence (DSE).

Module	M day	*r*	RMSE day
Moro Study (n = 38)			
DSSAT–CSM	−8.1	0.82***	11.5
Beta model with daily soil temperature	−5.6	0.84***	9.0
Beta model with daily air temperature	−0.9	0.85***	6.3
Beta model with hourly air temperature	−1.0	0.88***	5.8
Multi–Year, Multi–Site Study (n = 98)			
DSSAT–CSM	−3.8	0.59***	4.8
Beta model with daily soil temperature	−2.1	0.64***	3.5
Beta model with daily air temperature	0.3	0.73***	2.6
Beta model with hourly air temperature	0.3	0.72***	2.5
SPARC Studies (n = 20)			
DSSAT–CSM	−4.6	0.95***	5.1
Beta model with daily soil temperature	−2.3	0.88***	4.0
Beta model with daily air temperature	0.8	0.92***	2.2
Beta model with hourly air temperature	0.5	0.94***	1.7

***Significant at the 0.001 level.

emergence because the population dynamics affect seedling uniformity and vigour and therefore the final yield.

ACKNOWLEDGEMENTS

The authors of this paper would like thank our coop student Jae Hoon Saul for his technical support.

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