Library Copy -- 1997 #331

Base Temperature and Growing-Degree-Hour Requirements for the Emergence of Canola

Merle F. Vigil, R. L. Anderson, and W. E. Beard

Reprinted from *Crop Science*
Vol. 37, No. 3

Base Temperature and Growing-Degree-Hour Requirements for the Emergence of Canola

Merle F. Vigil,* R. L. Anderson, and W. E. Beard

ABSTRACT

Spring canola (*Brassica napus* L. and *B. rapa* L.) is sometimes planted when soil temperatures are below the optimum, causing farmers to have stand losses because of seed rotting in cold soil. Knowledge of the growing-degree hours (GDH) required for emergence of canola from different planting depths could help producers decide when and how deep to plant this crop. Our objectives were to quantify the base temperature (the minimum temperature required) for emergence, the number of GDH required for initial emergence of five cultivars of spring and winter canola, and to evaluate temperature × planting depth interactions of spring canola. 'Alto', 'Global', 'Tobin', 'Crystal', and 'Glacier' cultivars were planted 1 cm deep into pots of Weld silt loam (fine, montmorillonitic, mesic aridic Paleustolls). Pots were incubated at 0, 2, 4, and 16°C. Seedlings emerged were counted daily for all temperatures and twice daily during rapid emergence at 16°C. Simple-linear and segmented-nonlinear-regression were used to determine base temperatures and GDH requirements for initial emergence. Calculated base temperatures were between 0.4 and 1.2°C. Regardless of the constant temperature regime, emergence began between 1560 and 1940 GDH for the spring canola. Winter canola emerged at 1600 to 2800 GDH. Two cultivars (Tobin and Global) were also planted at 1-, 2-, 2.5-, 3-, and 4-cm depths and incubated at 4, 8, 12, and 16°C to investigate planting depth × temperature interactions. A reduction in emergence, as a function of an interaction between temperature and planting depth, was found for Global but not Tobin at the temperatures and planting depths used in this study. A match between the accumulated heat units in early spring for a location and the GDH required for initial emergence of the spring cultivars tested can be used to determine early spring canola planting dates. This analysis indicates that severe reductions in stand are possible when canola is planted at soil temperatures that are sustained much below 8°C. The heat unit approach used allows for the transfer of the relationships developed in this study to other locations.

M.F. Vigil, R.L. Anderson, and W.E. Beard, USDA-ARS, Central Great Plains Res. Stn., P.O. Box 400, Akron, CO 80720. Received 5 Feb. 1996. *Corresponding author (E-mail: mvigil@lamar.colostate.edu).

Published in Crop Sci. 37:844–849 (1997).

CANOLA is a potential oilseed crop for the Central Great Plains of the USA (Minor and Meinke, 1990). However, much of the basic agronomic knowledge required to make this crop successful in this region is inadequate. Management information such as cultivar adaptation, heat unit requirements, and planting date and depth have not been established. To develop management models for canola, heat unit and base temperature information is required.

Nykiforuk and Johnson-Flanagan (1994) reported significant reductions in the germination of canola at temperatures less than 10°C. Morrison et al. (1989), reported an overall base temperature of canola (cv. Westar) near 5°C. Wilson et al. (1992) found no germination at 2°C in a study of the germination of 11 *Brassica* forage cultivars. On the other hand, Kondra et al. (1983) reported up to 91% germination of canola at 2°C. Blackshaw (1991) reported that germination was greater than 70% at temperatures as low as 5°C, but that the time required for 50% emergence could be as long as 18 d. Others have reported similar findings (Acharya et al., 1983; Brar et al., 1991; Stewart et al., 1990, King et al., 1986).

Gbur et al. (1979) reported that the base temperature for grain sorghum [*Sorghum bicolor* (L.) Moench] germination could be determined by simple-linear regression of the germination rate per day on temperature. This method requires that data be collected from seed lots germinated in constant temperature incubators maintained at several different temperatures. The germination rate per day (GRPD) is calculated by dividing 50 by the days required to reach 50% germination. The GRPD is then regressed on temperature:

Abbreviations: EMERG, emergence; GDD, growing degree days; GDH, growing degree hours; GRPD, germination rate per day; RMSE, root mean square error; TEMP, temperature.

$$\mathrm{GRPD} = \beta_o + \beta_1(\mathrm{TEMP}), \quad [1]$$

where β_0 and β_1 are unknown fitted constants, GRPD is as described above and TEMP is temperature in degrees celcius. Since the base temperature corresponds to a mean development rate of zero, setting GRPD = 0 and solving for TEMP provides a base-temperature estimate denoted as α, we have:

$$\alpha = -\beta_o/\beta_1. \quad [2]$$

Gbur et al. (1979) argued that zero-germination data collected at temperatures below the base temperature are important for estimating the base temperature. They suggested a segmented-nonlinear-regression model as more appropriate, where a plateau equal to a height of zero is fit to all temperature data below the base temperature and a simple linear relationship is fit to the data above the base temperature. Instead of regressing GRPD on temperature, they suggest using the reciprocal of time (in days) to 50% germination:

$$1/\mathrm{time} = \beta_o + \beta_1(\mathrm{Temp}), \quad \text{if Temp} \geq \alpha$$
$$1/\mathrm{time} = 0 \quad \text{if Temp} \leq \alpha \quad [3]$$

where time is in days (d) and $\beta_o + \beta_1(\alpha) = 0$. In this case, the fitted straight line with a slope (β_1) of a value greater than zero will pass through the temperature axis at the base temperature α.

Knowledge of the base temperature is useful because it indicates the minimum temperature at which a seed will germinate. However, knowing the actual heat-unit requirement [growing degree hours (GDH) or growing degree days (GDD)] for emergence may be more useful. Knowledge of the heat-unit requirement, combined with knowledge of the expected heat-units for a region, allows for the successful match of appropriate cultivars and management practices for that region. Unfortunately, few studies in the literature indicate the heat unit requirements for the emergence of canola. Quantification of the heat unit requirement for emergence and the physiological development of these crops can be used by producers, researchers and extension personnel to make informed management decisions with respect to optimal spring planting dates. The objectives were to determine (i) the base temperature and heat unit requirements for the emergence of spring and winter canola, and (ii) investigate temperature × planting depth interactions on the emergence of spring canola.

MATERIALS AND METHODS

Experiment I

The emergence of three spring cultivars [Tobin (*B. rapa* L.), Alto (*B. napus* L.), Global (*B. napus* L.)], and two winter cultivars [Glacier (*B. napus* L.) and Crystal (*B. napus* L.)] was studied in a controlled environment incubator experiment. Approximately 20 kg of a Weld silt loam soil (fine, montmorillonitic, mesic aridic Paleustolls) was collected from the surface 10 cm of four separate field locations at the Central Great Plains Research Station near Akron, CO. Soils collected from each location were kept in separate prelabled containers, sieved with a 2-mm sieve to remove gravel, large organic matter, and weeds seed and then moistened to a gravimetric soil water content of 18 g g^{-1}. Soils were moistened by spreading the sieved soil out in a 1-cm-deep layer on a large plastic sheet. An aspirator bottle was used to wet the soil to the desired moisture content and then the soil was mixed by tumbling it back and forth on the plastic sheet (at least 10 times). The soil was then incubated at 25°C to induce germination of weed seed not removed. After 2 wk, weed seedlings were killed, the soil was mixed again, and was remoistened to 18 g g^{-1} gravimetric water content. The soil water content of 0.18 g g^{-1} (moisture tension of −35 Kpa) is approximately 40% water-filled-pore space. Soil collected from each separate field location was used for one replication of the experiment. The four separate field locations allowed for the establishment of four replications.

Individual 0.5-L clear plastic pots were marked at 1-cm intervals along the outside of each pot to indicate different planting depths. Each pot was then partially filled with 369.0 g of moist soil (soil water content of 0.18 g g^{-1}) equivalent to an oven dry weight of 312.7 g. The moist soil was packed to a wet bulk density of 1.2 Mg m^{-3} using the marks on the outside of the clear plastic pot as a guide. All cultivars of seed were treated with a carboxin (5,6-dihydro-2-methyl-*N*-phenyl-1,4-oxathiin-3-carboxamide)-captan {3a,4,7,7a-tetrahydro-2-[(tricholormethyl)thio]-1*H*-isoindole-1,2(2*H*)-dione} mixture at a rate of 2.6 g kg^{-1} of seed (Gustafson Inc., 1992)[1]. Twenty seeds of one cultivar were placed at equidistance spacings on the surface of the soil in individual pots and then covered with 85.8 g of moist soil (0.18 g g^{-1}) with an equivalent oven dry weight of 72.7 g. This soil was firmed over the seeds to a wet bulk density of 1.2 Mg m^{-3} and after firming, the seed was covered to a depth of 1 cm.

Each pot was covered with polypropylene plastic, held in place with a rubber band. The polypropylene was perforated at least 10 times with an icepick. The plastic reduced evaporative water loss from the pot yet the perforations allowed gas transfer. Using this technique in preliminary work, we found the evaporative water loss from a pot averaged 1.1 g over a 10-d period at 12 and 16°C (less than a 0.5% change in gravimetric soil water content). Since most of the emergence was complete after 7 d at these temperatures the soil water content in each pot was nearly constant for the duration of the emergence at those temperatures. At 2 and 4°C water loss averaged 0.9 g per pot over a 15-d period. Again soil water content was nearly constant and adequate for the duration of the experiment at the temperatures studied.

Enough pots were prepared to incubate five cultivars at four temperatures of 0, 2, 4, and 16°C in a complete factorial arrangement with four replications. A replication consisted of 20 pots (5 cultivars × 4 temperatures). The appropriate individual pots were then placed into separate Precision model-815 incubators (Precision Scientific Inc., Chicago, IL) without lights, set to the prescribed temperatures. These temperatures correspond to early spring soil temperatures in the Central Great Plains during the months of March and April.

The number of seeds emerged (hypocotyl just visible above the soil surface) in each pot were counted on a daily basis initially and then twice daily during the rapid emergence phase at 16°C. When approximately 10 seedlings had emerged, the perforated plastic cover was removed, seedlings were counted, the total number emerged was recorded, and all emerged seedlings were clipped at the soil surface to remove them from future counts. The clipping event was recorded and the perforated plastic cover was reattached with a rubber band. This made emergence counting easier with future counts.

[1]Use of company or trade names is for the benefit of the reader and does not imply endorsement of USDA-ARS of the products named nor criticism of similar ones not mentioned.

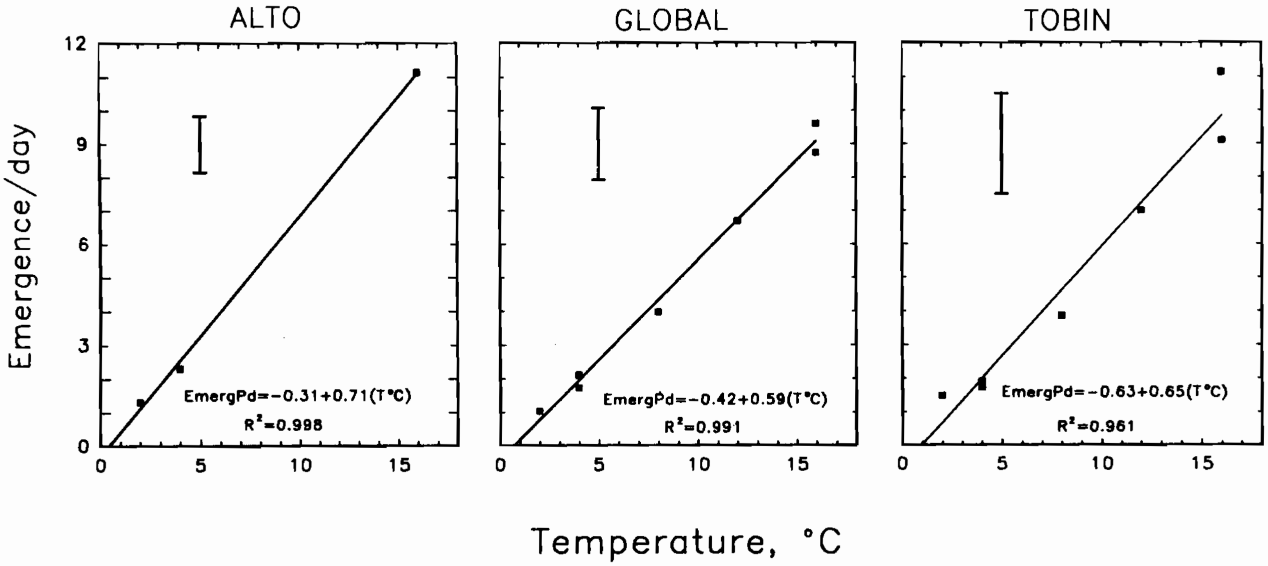

Fig. 1. The emergence rate (at 50% emergence) of spring cultivars of canola as a function of temperature. The symbols are the mean of four replications. The error bar is the largest standard error calculated at any temperature.

Experiment II

An additional experiment was conducted to evaluate temperature × planting depth interactions. The emergence of two spring cultivars (Global and Tobin) was tested as described above but at five planting depths (1, 2, 2.5, 3, and 4 cm) at 4, 8, 12, and 16°C. As with the earlier study emergence was recorded once daily at 4°C, but was recorded twice daily at 8, 12, and 16°C during the rapid emergence phase. This study was replicated four times in the same manner as with the first experiment.

A subset regression analysis procedure (PROC RSQUARE), (SAS, 1988) was used to regress emergence on planting depth (cm), temperature (°C) and the interaction between temperature and depth. Several mathematical transformations of temperature and depth (including depth, temperature and the product of temperature by depth raised to the 0.5, 0.75, 1.5, and 2 powers) were tried to find a best fit model between emergence and these variables. The model selected was the best fit model as determined by R^2 and root mean square error (RMSE), and the inclusion of an interaction term between temperature and planting depth. For simplicity, models containing more than three independent variables were not considered. The significance of the second and third independent variables as a predictor of emergence after adjusting for the other variables was tested using the method described by Weisberg (1980a).

Base Temperature and GDH Requirement Estimation

The data in Exp. I and Exp. II were combined to estimate GDH and base temperature. Emergence and accumulated heat units (GDH) were determined until emergence was complete for an individual treatment. Total emergence was defined as, the total number of seedlings emerged by 44 d after planting.

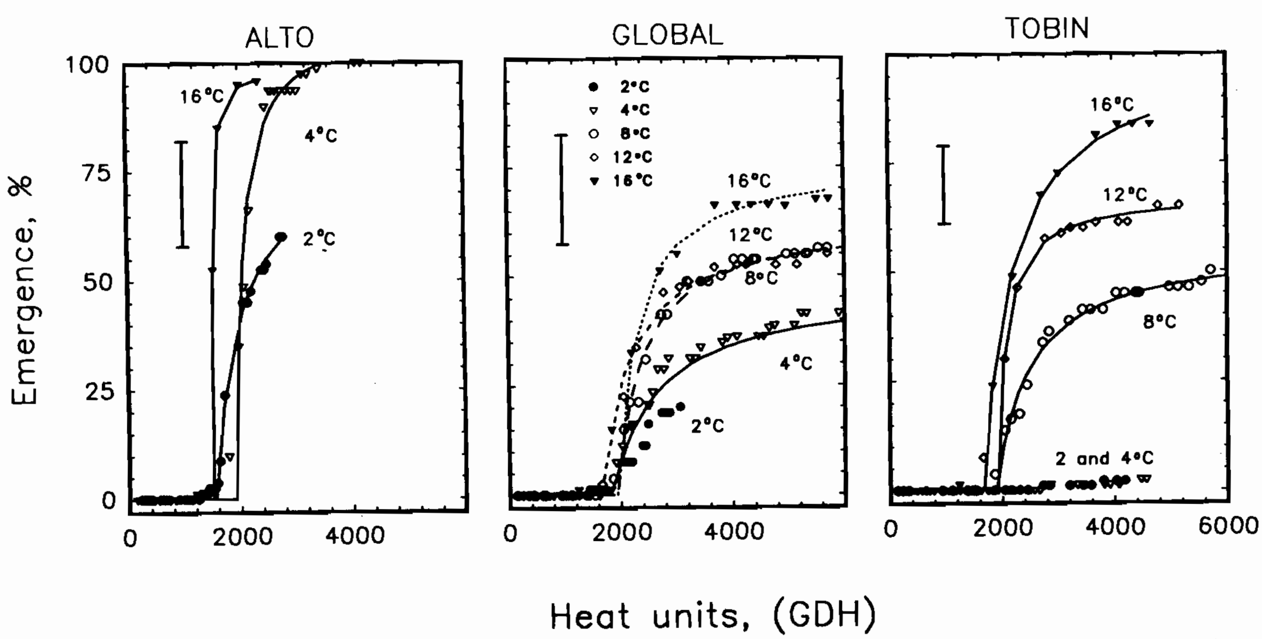

Fig. 2. Emergence of spring canolas as a function of accumulated heat units (GDH). The symbols are the mean of four replications. The line is the fitted-nonlinear-segmented-regression model: Emergence (%) = [A × (GDH − Xo)] / [(GDH − Xo) + B]. The error bar is the largest standard error calculated at any temperature and GDH.

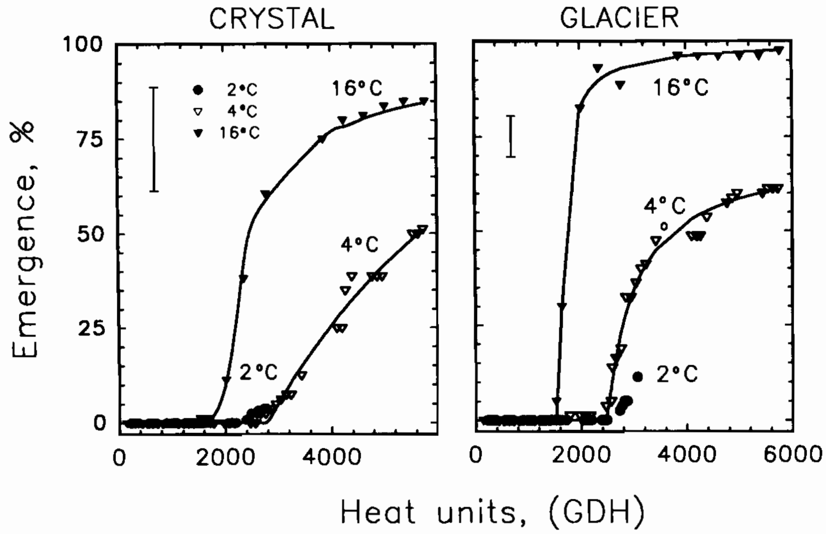

Fig. 3. Emergence of winter canolas as a function of accumulated heat units (GDH). The symbols are the mean of four replications. The line is the fitted-nonlinear-segmented-regression model: Emergence (%) = [A ×(GDH − Xo)] / [(GDH − Xo) + B]. The error bar is the largest standard error calculated at any temperature and GDH.

Fifty percent emergence was determined by linear interpolating when 50% of the total emergence had occurred (generally within the first 10 d after planting). The number of GDH required for initial emergence for a given cultivar and temperature was estimated by a segmented-nonlinear-regression similar to the Michaelis-Menton equation (Chang, 1981):

$$\text{EMERG} = [A \times (\text{GDH-}X\text{o})]/[(\text{GDH-}X\text{o}) + \text{B}] \quad \text{if GDH} \geq X\text{o}$$

$$\text{EMERG} = 0 \quad \text{if GDH} \leq X\text{o} \qquad [4]$$

where EMERG is the percent emergence, A is the estimated maximum emergence, GDH is as described above, Xo is the GDH required to initiate emergence and B is a fitted slope parameter. Equation [4] was fit to the emergence data as a function of GDH using a nonlinear regression procedure in SAS (SAS Institute, Inc. 1988). Base temperature was estimated using simple-linear and segmented-linear regression as proposed by Gbur et al. (1979) using Eq. [1], Eq. [2], and Eq. [3]. To determine significant differences between regression equation parameter estimates, the method described by Gomez and Gomez (1984) was used. To determine significant differences between base temperature estimates, the procedure described by Weisberg (1980b) was used.

RESULTS AND DISCUSSION

Canola emerged at temperatures as low as 2°C (Fig. 1), which agrees with the findings reported by Kondra et al (1983). However, emergence was significantly reduced at incubation temperatures of 4°C or lower (Fig. 2 and Fig. 3). Because estimated base temperatures for these cultivars were close to 0°C, segmented regression as described by Gbur et al. (1979) did not provide a different base temperature estimate than simple linear regression. Therefore, the simple linear regression technique given by Eq.[1] and Eq.[2] was used to estimate base temperatures (Table 1). The estimated base temperature for the spring cultivars was as low as 0.4°C (Table 1). The estimated base temperatures for the winter cultivars (Glacier and Crystal) were slightly higher (but not significantly higher with a t test at a probability level of 5%) than the spring cultivars. No emergence was measured at a temperature of 0°C for any of the cultivars tested.

The regression fit on all five cultivars combined provides an overall estimate of base temperature of 0.9°C (Table 1). The equations fitted to each individual cultivar were not significantly different than the equation fit to all of the data indicating that for practical purposes a single base temperature can be used for these cultivars. This estimated base temperature is 4°C lower than the "overall base" temperature previously reported by Morrison et al. (1989). The germination data reported by Morrison et al. (1989) was analyzed with Eq.[1] and Eq. [2] and a base temperature for germination of 2.3°C was calculated. By the same technique, the data reported by Blackshaw (1991) was analyzed and a base temperature of 1.6°C was calculated. The differences in the calculated base temperatures found in this study as compared to the other experiments may be a function of how

Table 1. Base temperature equations and base temperature estimates for five canola varieties.

Cultivar	Type	Regression equation	Base temperature °C	R^2	RMSE†	F
Alto	Spring	Emerg. = −0.31 + 0.71(T°C)	0.44	0.99	0.32	588.4**
Global	Spring	Emerg. = −0.42 + 0.59(T°C)	0.71	0.99	0.37	548.3**
Tobin	Spring	Emerg. = −0.63 + 0.65(T°C)	0.96	0.96	0.85	123.6**
Crystal	Winter	Emerg. = −0.58 + 0.53(T°C)	1.10	0.99	0.54	112.9**
Glacier	Winter	Emerg. = −0.85 + 0.71(T°C)	1.20	0.99	0.40	360.2**
All data‡		Emerg. = −0.56 + 0.63(T°C)	0.88	0.96	0.77	529.5**

† RMSE is the root mean square error. Regression equation F values followed by ** are significant at the 0.01 level of probability.

‡ Regression fit on the combination of all five varieties. The slopes and intercepts of the individual equations are not significantly different than those fitted in the "All data" equation at the 5% level of probability.

Table 2. Estimated GDH required for emergence (Xo) using segmented nonlinear regression.

Variety	Temperature °C	Parameter estimates† Xo‡	A	B	RMSE	R^2
Alto	2	1560	80	428	1.40	0.998
	4	1915	101	149	10.99	0.998
	16	1504	99	24	0.07	0.999
Global§	4	1729	56	975	3.34	0.995
	8	1936	63	468	3.27	0.998
	12	1644	64	548	3.07	0.998
	16	1937	76	363	18.09	0.993
Tobin	4	1755	39	1827	0.96	0.997
	8	1902	56	616	2.22	0.998
	12	1925	67	161	4.71	0.998
	16	1682	101	525	0.64	0.999
Glacier	4	2500	71	554	5.21	0.996
	16	1615	100	82	3.65	0.999
Crystal	4	2801	156	6150	4.43	0.993
	16	1956	96	524	2.73	0.999

† The parameter estimates are for the fitted equation: Emergence = A(GDH − Xo)/[(GDH − Xo) + B].
‡ Xo is the nonlinear regression estimate of the GDH required for initial emergence.
§ The modified Michaelis-Menton model could not describe the data for Global, Tobin, Crystal, and Glacier at temperatures of 2°C (nonlinear regression failed to converge).

Table 3. Percent emergence for the canola cultivars Tobin and Global at five planting depths and four incubation temperatures.

Temp. °C	Depth 1.0	2.0	2.5	3.0	4.0
	cm				
	TOBIN				
4	2.5 (2.9)†	2.5 (2.9)	3.8 (4.8)	2.5 (4.0)	3.8 (2.5)
8	51.3 (10.3)	46.3 (4.8)	40.0 (18.3)	42.5 (15.0)	48.8 (21.0)
12	61.3 (12.5)	75.0 (5.8)	61.3 (13.1)	66.3 (16.0)	62.5 (15.5)
16	76.3 (2.5)	71.3 (0.3)	77.5 (8.7)	66.3 (8.5)	76.3 (3.1)
	GLOBAL				
4	48.8 (16.5)	36.3 (13.1)	36.3 (12.5)	46.3 (10.3)	31.3 (7.5)
8	57.5 (6.5)	56.3 (6.3)	48.8 (11.1)	58.8 (4.8)	55.0 (9.1)
12	55.0 (5.8)	60.0 (8.1)	51.3 (6.3)	56.3 (6.3)	56.3 (7.5)
16	67.5 (13.2)	60.0 (10.8)	55.0 (10.8)	56.3 (13.1)	51.3 (6.3)

† Values in parentheses are the standard error of the mean of four replications.

the other experiments were conducted. The studies by Morrison et al. (1989) and Blackshaw (1991) were conducted at temperatures warmer than in this study. The lowest incubation temperature in the Morrison et al. (1989) study was 10°C and the lowest temperature in the Blackshaw study was 5°C. Neither of the other studies included incubation temperatures near the base temperature estimated in this study. It is conceivable that warmer incubation temperatures which are not close to the true base temperature would influence the fitted regression and base temperature calculation. Also, both of the other studies include only one cultivar. Morrison et al. (1989) studied 'Westar' (*B. napus*), a spring cultivar, and Blackshaw (1991) studied Glacier, a winter cultivar.

The GDH requirement for initial emergence was estimated with a modified Michaelis-Menton equation (Fig. 2 and Fig. 3). The GDH requirement for initial emergence is represented as the fitted *Xo* values given in Table 2. Heat unit requirements for the initial emergence of spring canola were between 1560 to 1940 GDH (Table 2 and Fig. 2). The GDH requirement appeared to be independent of incubation temperature for Global, Tobin, and Alto, whereas with Glacier and Crystal the GDH required decreased with increasing incubation temperature (Fig. 3 and Table 2). For Glacier and Crystal, emergence at 2°C was so reduced that nonlinear regression failed to converge and *Xo* could not be fitted. However, a visual interpretation of that data indicates that the GDH requirement for these cultivars at 2°C, is about the same as that fitted for 4°C (about 2200–2800 GDH). The reason emergence of the spring cultivars converges to a single GDH region, whereas the two winter cultivars appear to have a temperature-dependant GDH requirement is uncertain. The differences may simply be cultivar dependant.

Long-term average air temperatures, in the spring at our location, indicate that average soil temperature in the top 3 cm of soil is about 4°C the last week of March (Parton, 1984). Furthermore, the long-term data indicates an average accumulation of the required 1560 GDH between, 0100 am on 30 March and 1700 pm on 9 April (about 11 d). Between 0100 am on 30 March, and 0900 am on 12 April (about 13 d), an average of 1940 GDH are accumulated. From a practical standpoint, 10 to 12 d is not an unreasonable amount of time to wait for emergence. In general, as the duration for seedling emergence increases, there is a greater chance for damping off and other seed and seedling diseases to occur and therefore a greater chance for a loss in stand. How much earlier than March 30 can a farmer plant spring canola in the Central Great Plains region and still have a reasonable stand (100 plants m^{-2})? From the data in Fig. 2 and Fig. 3, one can observe a considerable reduction in total emergence, for the same number of GDH, at the lower incubation temperatures of 4 and 2°C. From this information, one can speculate that earlier plantings than the last week of March, when soil temperatures are cooler, will reduce stand. The average temperature the third week of March is 3°C. The average temperature for the first 2 wk of March is only 1°C at our location. Intuitively, one could expect considerable delayed emergence and a stand reduction if canola were planted the first and perhaps even the second week of March at our location. Other canola growing regions can use our accumulated GDH data with their own spring temperatures to estimate reasonable planting dates for spring canola. There is also the possibility that a heavier seeding rate in the early spring could be used to compensate for stand losses that would occur if planted too early. However that research has not been conducted yet and this is only speculation.

A reduction in the emergence of Tobin with increased planting depth was not observed to a depth of 4 cm (Table 3). This is important, because canola is generally sown at depths of 2.5 to 3 cm. Reduced emergence was observed with Global, with increased planting depth, at a temperature of 16°C but not at 4, 8 and 12°C. These results were surprising because Tobin seed is much smaller (440 seeds/ g) than Global (266 seeds/ g). Seed size, is generally positively correlated to successful emergence at greater planting depths (Janick, 1972). Regression of emergence by cultivar on planting depth, at each temperature yielded only one significant regression equation. This occurred with Global at a temperature of 16°C. The fitted equation was:

$$\text{EMERG} = 71.09 - 5.23(\text{DEPTH}) \qquad [5]$$

where EMERG is the percent emergence and DEPTH is the planting depth in cm. The R^2, RMSE, and F of regression were 0.91, 2.18 and 28.8 ($P < 0.02$), respectively. The lack of significant regression equations for emergence on planting depth for Tobin indicates that large reductions in stand will probably not occur if this cultivar is planted to a depth of 4 cm, provided soil temperatures are not maintained below 8°C for a long period of time. For Global, large reductions in stand will probably not occur if canola is planted to a depth of 3 cm. This would be true for soil bulk densities and soil moisture contents similar to those used in this experiment.

We used the subset selection procedure RSQUARE (SAS Institute, 1988) to evaluate the potential interaction between planting depth and temperature. The best fit, three parameter model that included an interaction term between temperature and depth, for the cultivar Global was:

$$\mathrm{EMERG} = -49.1 + 91.9(\mathrm{TEMP}^{0.5}) - 30.8(\mathrm{TEMP}^{0.75}) - 2.4(\mathrm{DEPTH}^{0.5} \times \mathrm{TEMP}^{0.5}) \quad [6]$$

where TEMP is temperature in °C and EMERG and DEPTH are as described earlier. The R^2, RMSE, and F of regression were 0.75, 4.89 and 16.1 ($P < 0.0001$), respectively. All three variables were significant predictors in the fitted equation. The significant inclusion of the $\mathrm{DEPTH}^{0.5} \times \mathrm{TEMP}^{0.5}$ term suggests an interaction between planting depth and temperature for this cultivar. In other words, low temperatures which tend to reduce emergence of this cultivar tend to have a greater effect on reducing emergence at greater planting depths.

The best fit, three parameter model that included an interaction term between temperature and depth, for Tobin was:

$$\mathrm{EMERG} = -2161 + 200(\mathrm{TEMP}^{0.5}) - 65.5(\mathrm{TEMP}^{0.75}) - 0.52(\mathrm{DEPTH}^{0.5} \times \mathrm{TEMP}^{0.5}) \quad [7]$$

The R^2, RMSE, and F of regression were 0.98, 4.35, and 261.6 ($P < 0.0001$), respectively. The interaction term was not a significant predictor in the fitted equation ($P < 0.45$). This suggests that no interaction between planting depth and temperature for Tobin occurred at the planting depths used in this study.

CONCLUSIONS

In this study, with the cultivars used, canola emerged at temperatures as low as 2°C with an estimated base temperature near 1°C. For temperatures greater than 2°C, the modified Michaelis-Menton equation describes 99% of the variability in emergence. The segmented equation provides an easy way to estimate the GDH requirement for the initial emergence of a given cultivar. A match between the accumulated heat units, in the early spring for Akron, CO, and the data set presented indicate that canola should be planted the last week of March. At that time of year, the average soil temperature in the top 3 cm of soil is near 4°C and gets progressively warmer with time. On average, this analysis suggests that increased seeding rates might be considered to offset expected reductions in emergence if canola is planted earlier in the spring when temperatures are cooler. For Tobin, depths of planting as great as 4 cm did not appear to reduce emergence. For Global, increased planting depth decreased emergence at 16°C, 5.2% for every additional centimeter of planting depth. This analysis indicates that severe reductions in stand are possible when canola is planted at soil temperatures that will be sustained much below 8°C. The heat unit approach used allows for the transfer of the relationships developed in this study to other locations.

ACKNOWLEDGMENTS

We thank and recognize Carolyn Brandon and Donna Fritzler (Ag. Research Technicians) for their thoughtful effort in helping to collect the data for this project.

REFERENCES

Acharya, S.N., J. Dueck, and R.K. Downey. 1983. Selection and heritability studies on canola/rapeseed for low temperature germination. Can. J. Plant Sci. 63:377–384.

Blackshaw, R.E., 1991. Soil temperature and moisture effects on downy brome vs. winter canola, wheat and rye emergence. Crop Sci. 31:1034–1040.

Brar G.S., J.F. Gomez, B.L. McMichael, A.G. Matches, and H.M. Taylor. 1991. Germination of twenty forage legumes as influenced by temperature. Agron. J. 83:173–175.

Chang R. 1981. Enzyme kinetics. p. 390–392. *In* Physical chemistry with applications to biological systems. Macmillan Publishing Co., New York.

Gbur, E.E., G.L. Thomas, and F.R. Miller. 1979. Use of segmented regression in the determination of the base temperature in heat accumulation models. Agron. J. 71:949–953.

Gomez K.A., and Gomez A.A. 1984. Homogeneity of regression coefficients. p. 372–379. *In* Statistical procedures for agricultural scientists. John Wiley and Sons, New York.

Gustafson, Inc. 1992. Grain and seed treating guide. 3rd ed. Gustafson, Inc., Plano, Texas.

Janick J. 1972. Seed propagation. p. 339. *In* Horticultural Science. 2nd edition. W.H. Freeman and Company, San Francisco.

King, J.R., Z.P. Kondra, and M.R. Thiagaraijah. 1986. Selection for fast germination in rapeseed (*Brassica napus* L. and B. campestris L.). Euphytica 35:835–842.

Kondra, Z.P., D.C. Campbell, and J.R. King. 1983. Temperature effects on germination of rapeseed (*Brassica napus* L. and B. campestris L.). Can. J. Plant Sci. 63:1063–1065.

Minor H.C., and L.J. Meinke. 1990. Canola production systems in the central U.S. region. p. 261–270. *In* Proc. International Canola Conf. p 261–270. Atlanta, GA. 2–6 April. Potash Phosphate Inst., Atlanta, GA.

Morrison, M.J., P.B.E. McVetty, and C.F. Shaykewich. 1989. The determination and verification of a baseline temperature for the growth of Westar summer rape. Can. J. Plant Sci. 69:455–464.

Nykiforuk, L. C., and A.M. Johnson-Flanagan. 1994. Germination and early seedling development under low temperature in canola. Crop Sci. 34:1047–1054.

Parton, W. J. 1984. Predicting soil temperatures in a shortgrass steppe. Soil Sci. 136:43–101.

SAS Institute, Inc. 1988. SAS/STAT User's guide, Release 6.03 edition. p 678–701. SAS Institute, Inc. Cary, NC.

Stewart, C.R., B.A. Martin, L. Reding, and S. Cerwick. 1990. Seedling growth, mitochondrial characteristics and alternative respiratory capacity of corn genotypes differing in cold tolerance. Plant Physiol. 92:761–766.

Wilson, R.E., E.H. Jensen, and G.C.J. Fernandez. 1992. Seed germination response to eleven forage cultivars of Brassica to temperature. Agron. J. 84:200–202.

Weisberg, S. 1980a. Hypotheses concerning one of the independent variables. p 49–50. *In* S. Weisberg (ed.) Applied linear regression. John Wiley & Sons, New York.

Weisberg, S. 1980b. Confidence intervals and tests. p. 19–22. *In* S. Weisberg (ed.) Applied linear regression. John Wiley & Sons, New York.