A Simulation Model of Cold Hardiness and Freezing Injury in Alfalfa as a Function of Cultivar Type

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Introduction

Alfalfa yield, persistence and profitability are affected adversely by winter injury in colder climates of North America. The extent of crop injury varies widely, causing large year-to-year fluctuations in yield and associated profitability. In years of adverse winter weather, production losses may amount to millions of dollars. By reducing yield and stand life, winterkill affects N fixation and soil-N uptake, thus influencing farm N budgeting and the environment. For these reasons, effects of winter injury cannot be ignored in alfalfa models, particularly when these models are to be used in whole farm simulators such as DAFOSYM for evaluating alternative management options in relation to production, profitability, or the environment.

Existing models of alfalfa lack winter injury effects or do not differentiate cultivar types for their differential response to winter survival and yield during multiple years of an alfalfa crop. ALSIM1, the alfalfa model used in DAFOSYM, does not simulate over-winter processes such as cold hardiness, freezing injury or stand loss. Consequently, output analyses of DAFOSYM lack winter-kill effects.

The objectives of this work were: (1) Develop a process-based module of cold hardiness and freezing injury for alfalfa. (2) Link the module to existing alfalfa growth models. (3) Validate the combined model (growth model + cold hardiness module) for predicting the effects of freezing injury on yield and stand life as a function of cultivar type and cutting managementduring 2-4years of continuous crop growth.

Model Development

Model structure and components. Cold hardiness and winter injury are newly developed. Other components in the model are adapted from existing models (Fick, 1981;Denison and Loomis, 1989). The state variables of the model include leaf blade, stem (includes flowers and seeds), buds, crown, root, and carbohydrate reserves.The processes include photosynthesis, shoot and root growth, dynamics of storage reserves, cold hardiness, freezing injury, and evapo-transpiration. The model simulates crop and soil processes daily.

Cold hardiness and freezing injury. Even though the mechanisms of dormancy and winter hardiness are not fully understood, studies have shown a strong correlation of cultivar dormancy characteristics to cold hardiness and winter survival (Cunningham et al., 1995; Jung et al., 1967; McCaslin, 1994; McKenzie et al., 1988; Schwab, 1993;Smith et al., 1986). These studies concluded that cultivar types of all dormancy ratings tolerated lower freezing temperatures as cold hardiness increased. However, cold-sensitive cultivars suffered higher rate of plant death at similar freezing temperatures compared to the winter-hardy cultivars. Based on these data, accumulation of cold hardiness was developed as a function ofcultivar type which in the model is characterized by fall dormancy rating (Fig. 1). Fall dormancy ratings (FDR) are supplied as user input. Cultivar ratings for dormancy are routinely published by the seed companies or are available from cultivar evaluation trials.Besides cultivar type, the rate of accumulation or break-up of cold hardiness is further modified by temperature and snow cover. Carbohydrate reserves affect cold hardiness accumulation only when the reserves in the root and crown fall below 10%. The process of winter acclimation resulting in cold tolerance is modeled with a simulatedcultivarhardiness index. Cold tolerance to freezing injury increases as the hardiness index increases.

Model inputs. Model requirements for user input data include: (a) daily weather (temperature, precipitation, and solar radiation), (b) soil (water holding capacity by layers), and (c) cultivar rating for fall dormancy.

Model Validation

Forage Yield Prediction. Field measured yield data were obtained from published sources (Djajanegara, 1990; Lang, 1985; Tesar, 1984) to test model predictions of forage yield. The validation data consisted of a total of 82 yield data representing different combinations of cultivars, production years, and cutting management systems at three locations across the north-central U.S. during 1977-90. Cutting schedules included 3, 4 or 5 harvests per yr. During the winters of 1988-89 and 1989-90, significant yield loss due to winterkill was observed in WI. Dormancy ratings for the cultivars tested varied between 2.5 and 4.0. Model predictions of yield were simulated for the corresponding field measured data by running the model for 2 to 4 years continuously.

The need for cold hardiness and winter injury simulation for predicting yield was tested by comparing model predictions of forage yield with or without winter injury components to the corresponding field data (Table 1). Values of (model-field) greater than zero represent over-predicted yields, while values less than zero represent under-predicted yields. Without winter injury simulation, yield was over-predicted by 0.95 Mg ha^{-1} cut^{-1} or 2.94 Mg ha^{-1} yr^{-1} compared to the corresponding field data (MOD$_{NO}$-FLD, all years, Table 1). During years of winterkill, over-prediction was greater (1.30 Mg ha^{-1} cut^{-1} or 5.83 Mg ha^{-1} yr^{-1}, 1988-90, Table 1), resulting in prediction errors of up to 50%.

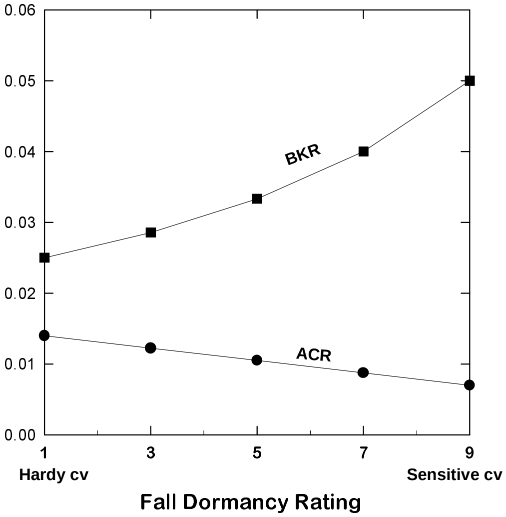

Figure 1. Potential rate of accumulation (ACR) or break-up (BKR) of cold hardiness for different cultivar types plotted as a function of fall dormancy rating (FDR). (Data derived from studies on accumulation of soluble sugars and protein in different cultivar types in response to freezing temperature.)

Simulation of cultivar hardiness to winter injury improved yield prediction significantly (MOD$_{NO}$-MOD$_{YES}$, Table 1). Model predicted yields were within 0.42 Mg ha^{-1} (14%) for individual harvests or 1.15 Mg ha^{-1} (8%) for annual yield compared to the field data (MOD$_{YES}$-FLD, all years, Table 1). During years of winterkill, prediction errors were within 8% (MOD$_{YES}$-FLD, 1988-90, 0.22 Mg ha^{-1} cut^{-1} or 0.99 Mg ha^{-1} yr^{-1}, Table 1).

Conclusion

(1) Simulation of cold hardiness and winter injury as a function of cultivar type improved forage yield prediction significantly. The model is capable of predicting yield in colder climates for different cultivar types managed under a variety of cutting schedules for 2 to 4 years continuously. (2) While this model was developed for use in DAFOSYM, other potential applications of the model include: (a) As a prediction tool to forecast winterkill each year. (b) As a tool in developing "cultivar maps" of winter injury for different cultivar types as a function of weather and cutting management.

Model availability. The model is written in FORTRAN 77. The computer code and documentation are available upon request.

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References

Cunningham, S.M., Volenec, J.J. & Teuber, L.R. (1995). Agron. Abstr., p.107, ASA, Oct.29, St. Louis, MO.

Denison, R.F. & Loomis, R.S. (1989). An integrative physiological model of alfalfa growth and development. Publication 1926. Univ. of California, Davis, CA.

Djajanegara, A.S. (1990). M.S. Thesis, Dep. of Agronomy, Univ. of Wisconsin, Madison, WI.

Fick, G.W. (1981). ALSIM 1 (LEVEL 2) user's manual. Agron. Mimeo 81-35. Cornell Univ., Ithaca, NY.

Jung, G.A., Shih, S.C. & Shelton, D.C. (1967). Cryobiology, 4, 11-16.

Lang, B.J. (1985). M.S. Thesis, Univ. of Wisconsin, Madison, WI.

McCaslin, M. (1994). p.134-136, Proc., 18th Forage Prod. & Use Symp., Wisconsin Forage Council, WI.

McKenzie, J.S., Paquin, R. & Duke, S.H. (1988). pp. 259-302. In: Hanson, et al. (ed) Alfalfa and Alfalfa Improvement, ASA, Madison, WI.

Schwab, P.M. (1993). M.S. Thesis. Univ. of Minnesota, St. Paul, MN.

Smith, D., Bula, R.J. & Walgenbach, R.P. (1986). Forage management. Kendall Publ., Dubuque, IA.

Tesar, M.B. (1984). pp. 59-65. In: National Alfalfa Symp., Michigan State University, E. Lansing, MI.

Table 1. Comparison of model predicted forage yield with the corresponding field measured data for a single harvest or for annual production.

	All years				Winterkill years (1988-90)			
-	Single harvest ($n^† = 62$)		Annual yield ($n = 20$)		Single harvest ($n = 18$)		Annual yield ($n = 4$)	
Abbreviation and description	mean	s.d.‡	mean	s.d.	mean	s.d.	mean	s.d.
	— $Mg\ ha^{-1}$ —		— $Mg\ ha^{-1}$ —		— $Mg\ ha^{-1}$ —		— $Mg\ ha^{-1}$ —	
FLD: field measured data	2.90	1.39	13.63	3.83	2.60	1.33	11.68	1.85
MOD_{NO}: model without cold hardiness and winter injury	3.85	1.42	16.57	3.31	3.89	1.45	17.51	3.44
MOD_{YES}: model with cold hardiness and winter injury	3.32	1.37	14.77	3.08	2.81	1.44	12.66	1.41
MOD_{NO}-FLD: MOD_{NO} compared to field data	0.95	0.99	2.94	3.26	1.30	0.89	5.83	2.99
MOD_{YES}-FLD: MOD_{YES} compared to field data	0.42	0.80	1.15	1.80	0.22	0.82	0.99	1.20
MOD_{NO}-MOD_{YES}: Without or with winter injury	0.53§	0.69	1.80¶	2.48	1.08§	0.83	4.85#	3.86

†n = number of data; ‡ s.d. = standard deviation of the mean; § $P < 0.0001$; ¶ $P < 0.005$; # $P < 0.1$