# Crop Models for DAFOSYM

## *Cold Hardiness and Winter Injury in Alfalfa*

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Content



### Introduction

Alfalfa yield, persistence and profitability are affected adversely by winter injury in the colder climates of North America (Smith et al. 1986; McKenzie et al. 1988).The extent of crop injury varies widely, causing large year-to-year fluctuations in yield and associated profitability. Severe yield reduction due to winter injury was observed on about 30-60% of the total acreage under alfalfa in Wisconsin during 1988-89 to 1992-93 (Miller 1994). By reducing yield and stand life, winter injury affects N fixation and soil N uptake (Vance et al. 1988), thus influencing farm N balance and the environment. For these reasons, effects of winter injury cannot be ignored in growth models, particularly when these models are used in whole farm simulators such as DAFOSYM (Rotz et al. 1989) for evaluating alternative management options in relation to farm profitability or the environment. In such cases, models need to predict forage yield continuously for at least 2-4 years of crop life incorporating the effects of winter injury.

Existing models of alfalfa lack winter injury effects, or do not differentiate cultivars for their differential response to winter survival and yield during multiple years of an alfalfa crop. The ALSIM 1 (Level 2) alfalfa model (Fick 1981) has been used widely in the colder climates of North America (Parsch 1987; Rotz et al. 1989). However, the model does not simulate yield loss due to winter injury. While adapting it to the Canadian conditions, Bourgeois et al. (1990) observed that the model failed to distinguish cultivars with respect to their stand persistence or yield. For

Table 1.
User input data required in the model.

| | |
|---|---|
| Daily Weather: | |
| | Maximum and minimum air temperature (°F or °C) |
| | Solar radiation (Ly) |
| | Precipitation (inch or mm) |
| Cultivar: | |
| | *Fall Dormancy Rating (*FDR*)* |
| Soil/Site/Management: | |
| | Latitude (degrees) |
| | Root zone depth (cm) |
| | Soil water holding capacity (by layers) (v/v) |
| | Harvest dates |

better yield prediction, the authors suggested that models need to simulate cultivar hardiness to winter injury.

To address the aforementioned concerns, a simulation model of alfalfa is needed in which winter hardiness and winter injury are integrated with other factors of crop growth. Most existing models of alfalfa (ALSIM 1 (Level 2), Fick 1981; GROWIT, Neels 1981; SIMED, Holt et al. 1975; SIMFOY, Selirio and Brown 1979) lack these processes or their interaction with weather and management during multiple years of crop life. The ALFALFA model (Denison and Loomis 1989) simulates population dynamics and cold tolerance, but lacks cultivar specificity (e.g., winter hardy vs. sensitive) to winter survival and yield. While these models may be inappropriate to predict winter injury effects on forage yield, it should be emphasized that these models were used successfully to address problems for which they were developed (Fick et al. 1988). Besides, these models provide component procedures and parameters for use in the construction of new models. Several components of the model described in this paper were adapted from ALSIM 1 (Level 2) and ALFALFA models.

The objective of this study was to develop a process-based sub-model of winter injury for alfalfa to permit prediction of forage yield continuously for 2-4 years of crop life as a function of weather and cultivar characteristics. The objective was carried out in three steps: (1) A simple sub-model of cold hardiness and winter injury was developed using standard cultivar information on fall dormancy. (2) The sub-model was integrated into an alfalfa growth model which was largely constructed from existing alfalfa models. (3) The combined model (growth model with winter injury sub-model) was checked for accuracy by predicting the effects of winter injury on forage yield observed in field studies.

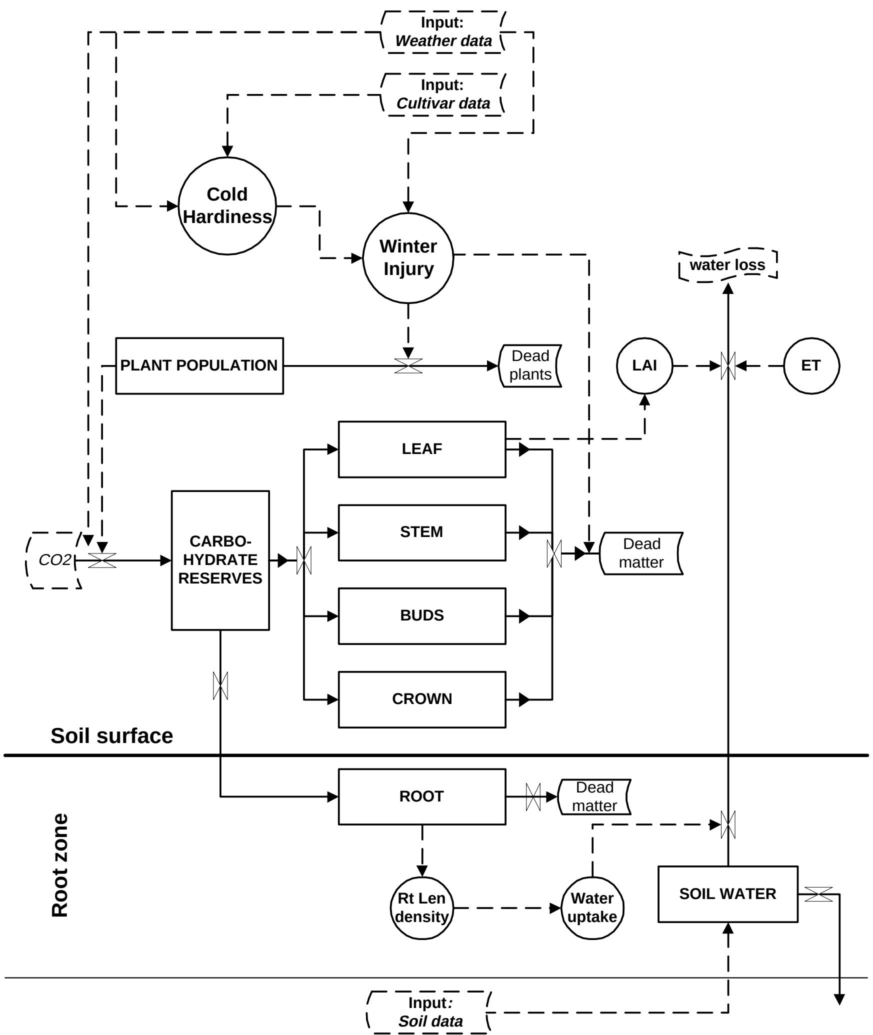


*Figure 1. A simplified schematic representation of the alfalfa model. (Solid-line boxes represent model states; dashed-line boxes, input/output; circles, auxiliary variables; solid lines with arrows, material flow, and dashed lines with arrows, information flow.)*

# Model Development

## *Model Structure and Components*

A simplified schematic representation of the model showing the major components and their inter-relationships is presented in Fig. 1. The model divides the plant into leaf, stem (includes flowers and seeds), buds, crown, root and carbohydrate reserves. Simulated crop processes include photosynthesis, shoot and root growth, dynamics of storage carbohydrate reserves, cold hardiness, winter injury, and evapo-transpiration. The model simulates growth daily using readily available weather, cultivar and soil data as user inputs, which are listed in Table 1.

Simulation of cold hardiness and winter injury is newly developed, and is discussed in detail later. Other components in the model are adapted from existing models, and a brief description

*"Partitioning of daily growth into leaf, stem, bud, crown or root is based on procedures of ALSIM 1 and ALFALFA models."*

*"Winter hardiness refers to the ability of the crop to withstand the effects of all stresses during winter."*

follows: Daily supply of photosynthates (carbohydrates) is modeled by canopy photosynthesis (Denison and Loomis 1989, Spitters 1986). Partitioning of daily growth into leaf, stem, bud, crown or root is based on procedures of ALSIM 1 and ALFALFA models. Evapo-transpiration (ET) is modeled as a function of temperature, radiation, soil water, and leaf area based on the ET models of Ritchie (1972). Water stress effects on crop growth are simulated with a stress index based on ET, as explained in the ARID CROP model (van Keulen et al. 1981) and used in WANGRO (Kanneganti and Fick 1991). Soil water movement is based on a simple, capacity-type modeling approach (Addiscott and Wagenet 1985). Water moves down from one layer to the next below, after filling up the first layer to field capacity. Soil temperature is estimated from annual air temperature curves (Williams et al. 1984). The effect of snow cover resulting in higher soil temperature under snow compared to temperature observed in bare soils (without snow) is computed as a function of snow depth (McKenzie and McLean 1984, McKenzie et al. 1988).

A copy of the computer model with documentation, source code and sample files can be obtained from the author (details in the Appendix).

## Cold Hardiness and Fall Dormancy

### Winter Hardiness

Alfalfa crop when subjected to temperatures below 32 °F during summer cannot survive the freezing stress. However, the same crop is able to withstand temperatures as low as -5 °F in the winter following the development of winter hardiness during the fall. Winter hardiness refers to the ability of the crop to withstand the effects of all stresses during winter. Lack of adequate winter hardiness results in winter injury which affects crop production in the subsequent growing season. Winter injury can range from total plant kill to reduced growth due to plant weakening. Several factors that are related to weather, soil or crop management may contribute to winter injury. Some of the more common factors include freezing temperatures, pests and diseases, poor soil drainage, soil heaving, ice sheeting, inadequate soil fertility, or poor timing and frequency of harvesting (Smith et al., 1986). Among these, injury caused by freezing temperatures is by far the most common cause of winter injury in the colder climates. Plants that have a greater tolerance to freezing stress are referred to as having high cold hardiness. Plants with high cold hardiness have a better chance to survive in cold climates (winter hardiness).

### Cold Hardiness

During the hardening period in the fall, the crop undergoes internal (biochemical and physiological) and external (morphological) changes that seem to increase crop tolerance to winter stresses while decreasing growth. As crop hardening progresses, concentrations of total sugars (mostly sucrose), amino acids (predominantly proline) and fatty acids (linoleic and linolenic) in the crown and root increase, with peak concentrations often coinciding with the maximum level of cold tolerance (i.e., lowest temperature tolerance) observed for a cultivar. Morphological changes include prostrate and rosette-like growth compared to erect growth of the same species during spring and summer. These morpho-physiological changes accompanied by reduced growth in the fall constitute the fall dormancy characteristics of alfalfa. In general, dormancy is characterized by reduced biochemical and physiological activities, suppressed growth, and increased resistance to withstand stress. Several studies have shown a very strong association of fall dormancy characteristics to cold or winter hardiness and winter survival (Cunningham et al. 1995, Schwab 1993, Stout et al. 1992). However, the causal mechanisms for such an association are not clearly understood.

Different cultivars show varying levels of tolerance to freezing or other winter stresses suggesting a genetic control on the level of hardiness that a cultivar can express. Cultivars also seem to differ in their requirement for the length (duration) of hardening in the fall. Hardy cultivars which are characterized by greater levels of dormancy characteristics initiate hardening earlier in the fall and achieve greater levels of hardiness

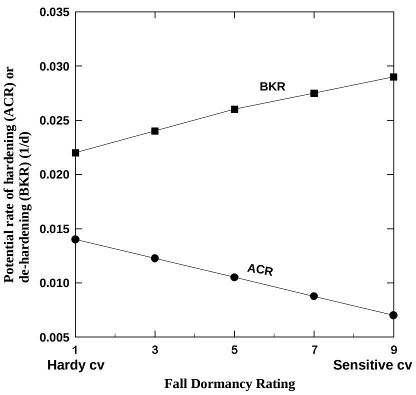


*Figure 2. Potential rate of hardening (ACR) or dehardening (BKR) for different cultivars plotted as a function of fall dormancy rating (FDR).*

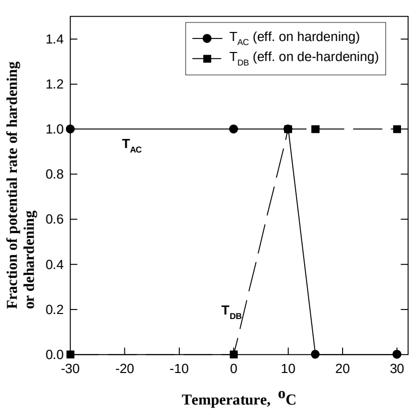


*Figure 3. Effect of temperature on rate of hardening ($T_{AC}$) or dehardening ($T_{DB}$).*

in a shorter period compared to the less-hardy types (Jung et al. 1967, Duke and Doehlert 1981, Paquin and Lechasseur 1982). However, during spring temperatures rise, hardy types deharden over a longer period compared to the less hardy types, an adaptation that seems to help the former types to resist freezing injury for a longer period. Dehardening is opposite of hardening, and refers to declining hardiness accompanied by a reversal of dormancy characteristics.

## Fall Dormancy

Differences in fall growth exist among cultivars because of fall dormancy. A simple numeric scale has been developed to differentiate dormancy expression among cultivars (Barnes et al. 1992). The scale is based on the height of about 40 d of regrowth following a cutting in early September. Values for the scale range from 1.0 (0-2" of regrowth) for the highly dormant cultivars to 9.0 (regrowth of 16" or greater) for the least dormant types, with intimidate values differing in 2 inches of regrowth per unit of the scale. Due to the inverse relationship between fall growth and dormancy which is strongly associated with winter hardiness, the scale is often used as an index for a cultivar's winter hardiness potential. These growth scores are also referred to as fall dormancy ratings (FDR), and are routinely published by seed companies or are available from cultivar evaluation trials conducted by the universities (Undersander et al. 1995).

While the potential rate of hardening and the maximum level of cold hardiness are under genetic control, their expression is influenced greatly by weather factors, particularly temperature. Daily average temperatures between 32 and 50 °F promote dormancy characteristics and hardening while higher temperatures result in dehardening (Jung et al. 1967, McKenzie and McLean 1980, 1984). In general, factors promoting fall dormancy seem to increase hardiness while suppressing growth.

In recent years, breeding programs have been focusing on altering the association between fall dormancy and winter hardiness in an effort to increase growth during fall and spring while maintaining winter hardiness (McCaslin 1994).

## Modeling Cold Hardiness

Since cold hardiness is a major contributor to winter hardiness and winter survival in the colder climates, the model assumes that winter injury can be predicted adequately as a function of cold hardiness. The processes of cold hardening are described mathematically using the quantitative information available on dormancy characteristics as discussed in the foregoing. Consequently, the model assumes the existence of a strong association between fall dormancy and winter hardiness. A need for the simulation of other winter injury factors will be determined following an extensive testing of the current version for its accuracy of winter injury prediction.

The model uses fall dormancy rating (FDR) of a cultivar to represent its genetic potential for maximum cold tolerance. Fall dormancy ratings are provided in the model as user input (Table 1). Initiation of cold hardening during the fall is triggered by a critical daylength, which decreases from about 12 hr for the highly dormant cultivars (i.e., FDR=1) to about 9 hr for the least dormant types (FDR=9). After hardening is initiated, duration required for the crop to change from a normal condition to a fully hardened condition varies with cultivar. Potential rates of hardening (observed mostly in the fall) or dehardening (in the spring) for different cultivars grouped by FDR are shown in Fig. 2. These data are derived from cold tolerance response data of alfalfa exposed to freezing temperatures in field or in laboratory (Jung et al. 1967, Duke and Doehlert 1981, Paquin and Lechasseur 1982). Cultivars of contrasting fall dormancy ratings were used in these studies.

Besides genetic control which is accounted for in the model by FDR, hardening processes are greatly influenced by temperature. Effect of temperature on the rate of hardening or dehardening is shown in Fig. 3, data for which were obtained from cold tolerance studies conducted in different cultivars (Jung et al. 1967, McKenzie and McLean1980, 1984, McKenzie et al.1988). Average

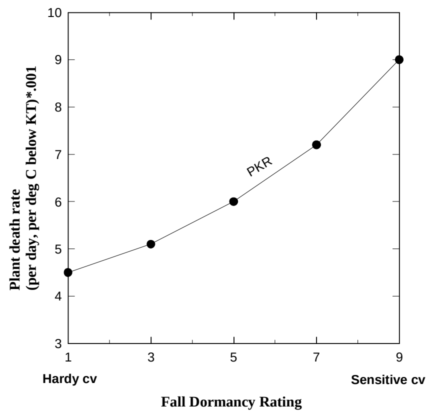


*Figure 4. Potential rate of plant death (PKR) for different cultivars plotted as a function of fall dormancy rating (FDR). (KT = Killing Temperature, Table 2.)*

***"A cultivar is assumed to have achieved its maximum level of hardiness when the cumulative hardiness index reaches a value of 1.0 ..."***

***"... cultivars of all dormancy ratings tolerate lower freezing temperatures as cold hardiness increases."***

daily temperatures below 50 ºF promote cold hardening while temperatures above 50 ºF promote dehardening (Eq. 1 and 2, Table 2).

The physiological status of a crop with respect to carbon reserves may also influence the rate of hardening. Non-structural carbohydrate reserves in the root and crown affected cold hardiness, but only when the reserves dropped to very low levels (Jung and Smith 1960, Smith et al. 1986). At higher concentrations, reserves did not show any significant correlation with winter hardiness (Cunningham et al. 1995). Based on these data, rate of hardening is affected in the model only when the reserves fall below 10% ($R_o$, Eq. 1, Table 2).

Cold tolerance increases as hardening progresses, and this process is represented in the model by a cumulative variable, termed Hardiness Index (HI, Eq. 3, Table 2). A cultivar is assumed to have achieved its maximum level of hardiness when the cumulative hardiness index reaches a value of 1.0, while a value of zero for HI represents a dehardened condition. Intermediate values for HI represent intermediate stages of cold tolerance.

## Modeling Winter Injury

Data from a series of winter injury studies conducted in alfalfa with cultivars of contrasting fall dormancy rating under severe ("test") winter conditions (McKenzie and McLean 1980, 1982, 1984; Paquin and Lechasseur 1982) were used to model winter injury as a function of cultivar, its cold hardiness condition and freezing temperature. These studies concluded that cultivars of all dormancy ratings tolerate lower freezing temperatures as cold hardiness increases. However, the least dormant cultivars suffer higher rates of mortality at similar freezing temperatures compared to the highly dormant cultivars. Based on these data, a potential rate of plant death was computed for different cultivars grouped by FDR (Fig. 4), a process which accounts for winter injury due to plant mortality.

Table 2.
Cold hardiness and winter injury dynamics in alfalfa.

Cold Hardiness:
Hardening:
$D_C$ = *ACR*min*($T_{ac}$, $R/R_o$, 1.), *(Eq. 1)*
ACR = Potential rate of cold hardening. ($d^{-1}$) [Fig. 2]
$T_{ac}$ = Effect of temperature on rate of cold hardening. [Fig. 3]
R = Carbohydrate reserves in root and crown. (kg $kg^{-1}$)
$R_o$ = Reserves limiting rate of cold hardening. (0.1 kg $kg^{-1}$)

De-hardening:
$D_B$ = BKR*$T_{db}$ (Eq. 2)
BKR = Potential rate of de-hardening. ($d^{-1}$) [Fig. 2]
$T_{db}$ = Effect of temperature on rate of de-hardening. [Fig. 3]

Cold hardiness Index:
HI = $\sum (D_C - D_B)$, (Eq. 3)
HI = Level of cold hardiness (tolerance) in a cultivar. Range: 0.0 to 1.0.
$D_C$ = Rate of hardening. ($d^{-1}$)
$D_B$ = Rate of de-hardening. ($d^{-1}$)

Winter Injury:
KT = $T_{kt}$*(HI+1) (Eq. 4)
*WI* = *PKR*max(0., KT-SST),* *(Eq. 5)*
WI = Plant death coefficient. ($d^{-1}$)
PKR = Potential rate of plant death. ($d^{-1}$ (°C below KT)$^{-1}$) [Fig. 4]
KT = Critical temperature below which plant death occurs. (°C)
$T_{kt}$ = Temperature above which winter injury is insignificant. (-4.0 °C)
SST = Soil-surface temperature. (°C)

***"Carbon reserves may become limiting if the crop experiences intermittent warm and cold periods such as during early spring."***

***"Simulation of winter injury improved yield prediction significantly ..."***

Effects of plant weakening resulting in reduced spring growth are accounted in the model indirectly as a function of carbon reserves in the crop. Initial growth during spring, until enough leaf area accumulates, is dependent upon the availability of carbon reserves in the crown and root. Therefore, growth can be slower under situations of limiting reserves. Carbon reserves may become limiting if the crop experiences intermittent warm and cold periods such as during early spring. Warm weather promotes dehardening which is associated with reserve utilization for new growth, and a subsequent spell of freezing temperatures may cause winter injury resulting in a net loss of carbon reserves.

Simulation of winter injury as a function of cultivar and its cold hardiness condition is summarized in Eq. 4 and 5 (Table 2). The critical temperature below which plant death occurs is termed as killing temperature (KT, Eq. 4, Table 2), and is calculated as a function of cultivar Hardiness Index (HI, Eq. 1, Table 2). Crop tolerance to freezing temperatures increases as HI increases, but the maximum freezing stress that a crop can withstand is determined by a combined effect of HI and cultivar (Eq. 5, Table 2). When the temperature drops below KT, plants die at a cultivar-specific rate (Fig. 4) and in proportion to temperature drop below KT (Eq. 5, Table 2). Thus, susceptibility to winter injury is modeled as a function of cultivar genetics, state of cold hardiness, and the magnitude and duration of freezing temperatures. As a result of several possible interactions among these factors, different cultivars harden and deharden at different times and rates during the fall, winter and spring exposing the model crop to varying degrees of winter injury.

Table 3.
Characteristics of field measured data used for model validation.

| State: Location | Cultivar | Cutting mgmt. | Producion yr. | Calendar yr. | Source |
|---|---|---|---|---|---|
| | | cuts $yr^{-1}$ | | | |
| MI: E. Lansing | Honeoye | 4 | 1,2,3 | 1977-80 | Tesar,1984 |
| MI: E. Lansing | Big-10 | 4 | 1,2 | 1980-82 | Tesar, 1984 |
| MI: E. Lansing | Pio531,WL316 | 4 | 1,2,3 | 1982-85 | Tesar, 1984 |
| WI: Arlington | Blazer | 3, 4, 5 | 1,2 | 1982-84 | Lang, 1985 |
| WI: Prairie-du-Sac | Dart | 4, 5 | 1,2 | 1988-90 | Djajanegara, 1990 |

# Model Testing

The ability of the model to predict forage yield loss due to winter injury was tested by comparing model predictions of forage yield with or without winter injury simulation to field data. Field data were obtained from published sources, and consisted of a total of 82 yield measurements representing different combinations of cultivars, production years and cutting management systems at three locations across the north-central US during 1977-90 (Table 3). Cutting schedules included 3, 4 or 5 harvests per year. During the winters of 1988-89 and 1989-90, significant yield loss due to winter injury was observed in Wisconsin (Martin et al. 1991). Dormancy ratings for the cultivars tested varied between 2.5 and 4.0. Model predictions of forage yield were simulated for the corresponding field data by running the model for 2 to 4 years continuously.

Field data and the corresponding model predicted yield data were paired, and descriptive statistics were computed for field data, model predictions, or their difference (model-field) for individual harvest or for annual yield (Table 4). Values of (model-field) greater than zero represent over-predicted yields, while values less than zero represent under-predicted yields. For a perfect model, the difference (model-field) should equal zero. Without winter injury simulation, yield was over-predicted by 0.42 tons $acre^{-1}$ $cut^{-1}$ or 1.31 tons $acre^{-1}$ $yr^{-1}$ compared to the corresponding field data (Table 4, Line D; $MOD_{NO}$-FLD, all years). During years of winter injury (1988-90), over-prediction was greater (Table 4, Line D; 0.58 tons $acre^{-1}$ $cut^{-1}$ or 2,60 tons $acre^{-1}$ $yr^{-1}$), resulting in prediction errors of up to 50%.

Simulation of winter injury improved yield prediction significantly (Table 4, Line E; $MOD_{YES}$-FLD). Predicted yields were within 0.19 tons $acre^{-1}$ (14%) for individual harvest or 0.51 tons $acre^{-1}$ (8%) for annual yield compared to the

**Table 4**
**Comparison of model predicted forage dry matter yield with the corresponding field data for a single harvest or for annual production (field data from sources listed in Table 3).**

| Abbreviation and description | All years: Single harvest (n† = 62) mean | s.d.‡ | All years: Annual yield (n = 20) mean | s.d. | Winterkill years (1988-90): Single harvest (n = 18) mean | s.d. | Winterkill years (1988-90): Annual yield (n = 4) mean | s.d. |
|---|---|---|---|---|---|---|---|---|
| | — tons/acre — | | — tons/acre — | | — tons/acre — | | — tons/acre — | |
| A. FLD: field measured data | 1.29 | 0.62 | 6.08 | 1.71 | 1.16 | 0.59 | 5.21 | 0.83 |
| B. $MOD_{NO}$: model without winter injury | 1.72 | 0.63 | 7.39 | 1.48 | 1.73 | 0.65 | 7.81 | 1.53 |
| C. $MOD_{YES}$: model with winter injury | 1.48 | 0.61 | 6.59 | 1.37 | 1.25 | 0.64 | 5.65 | 0.63 |
| D. $MOD_{NO}$-FLD: $MOD_{NO}$ compared to field data | 0.42 | 0.44 | 1.31 | 1.45 | 0.58 | 0.40 | 2.60 | 1.33 |
| E. $MOD_{YES}$-FLD: $MOD_{YES}$ compared to field data | 0.19 | 0.36 | 0.51 | 0.80 | 0.10 | 0.37 | 0.44 | 0.54 |
| F. $MOD_{NO}$-$MOD_{YES}$: Without or with winter injury | 0.24§ | 0.31 | 0.80¶ | 1.11 | 0.48§ | 0.37 | 2.16# | 1.72 |

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

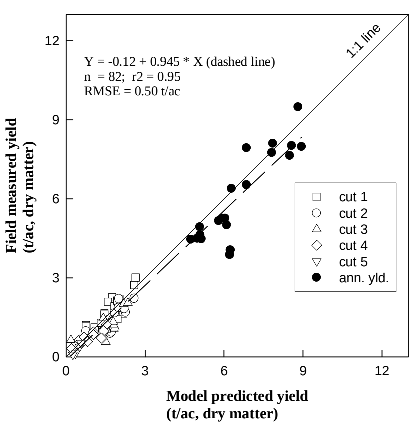


*Figure 5. Comparison between model-predicted and the corresponding field-measured forage yield for individual harvest or for annual production. (Dashed line is the regression line, solid diagonal line is the 1:1 line. Field data are from sources listed in Table 3.)*

field data (Table 4, Line E; $MOD_{YES}$-FLD, all years). During years of winter injury, prediction errors were within 8% (Table 4, Line E; $MOD_{YES}$-FLD, 1988-90, 0.10 tons acre$^{-1}$ cut$^{-1}$ or 0.44 tons acre$^{-1}$ yr$^{-1}$). An average yield loss of 2.16 tons acre$^{-1}$ yr$^{-1}$ due to winter injury was predicted in years of severe winter injury (Table 4, Line F; $MOD_{NO}$-$MOD_{YES}$).

Prediction accuracy for yield was estimated by comparing field-measured yield with model predictions of the same data (Table 4; FLD (Line A) vs $MOD_{YES}$ (Line C), all years, n=82). A plot of these data are shown in Fig. 5. If the model was perfect, all data points would fall on the 1:1 line. Ninety-five percent of the measured variability in yield was predicted by the model (Fig. 5), indicating a good agreement between field and predicted data. Yield was predicted with a standard deviation of 0.50 tons acre$^{-1}$ (Fig. 5).

## Conclusion

Alfalfa yield, persistence and profitability are affected adversely by winter injury in the colder climates of North America. Existing models of alfalfa lack winter injury effects, or do not differentiate cultivars for their differential response to winter survival and yield. A process-based simulation model of cold hardiness and winter injury was developed to predict alfalfa yield as a function of weather, cultivar and management. Simulation of cold hardiness and winter injury improved model predictions of yield for different cultivars of varying fall dormancy rating. Ninety-five percent of the measured variability in forage yield was predicted by the model. Predicted yield was within 0.2 tons/acre for individual harvest or 0.5 tons/acre for annual yield compared to field-measured yield. An average yield loss of 2.1 tons/acre per year due to winter injury was predicted in years of adverse winter weather.

While this model was developed primarily for use in DAFOSYM, other potential applications of the model are: (a) as a prediction tool to forecast winter injury; (b) as a tool in developing winter injury maps for different combinations of cultivars and cutting management in relation to weather; (c) as a platform for studying the effects of alternative relationships among fall dormancy, cold hardiness and winter injury on forage yield. Some of these applications are currently in development.

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# Appendix

Model Availability:

The model is written in FORTRAN 77 using the Microsoft[1] FORTRAN compiler. The program runs on personal computers running DOS 3.1 or higher. The computer code, documentation, and sample data files are available upon request from the author.

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