A WEB-BASED MODEL FOR ESTIMATING WINTER SURVIVAL IN CEREALS

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Abstract

An interactive web-based model for estimating winter survival in cereals has been developed for use by farmers, extension workers, and researchers. The model is based on a series of equations that describe acclimation, dehardening, and damage due to low-temperature stress that are consistent with recent interpretation of low-temperature gene regulation. Low-temperature tolerance is estimated on a daily basis relative to stage of phenological development and cultivar cold hardiness potential. The model has been field validated for cereals in Saskatchewan and has been used in the simulation of over wintering for a wide range of species. Because it complies with the known low-temperature responses of cereals and is fully interactive, it can be used as a teaching tool that allows production risks, cause-and-effect processes, and genetic theories to be systematically investigated.

Background and Operation

The following information is provided to give the user an understanding of the input requirements and the practical applications of the web based model for estimating winter survival in cereals (http://www.usask.ca/agriculture/plantsci/winter_cereals/index.php). Additional details on the theory behind and operation of the underlying model can be found in an earlier publication (Fowler et al. 1999). The input requirements of the model are genetic coefficients that determine the plant's stage of phenological development and cold hardiness potential plus daily measurements of soil temperature. The model uses these inputs to estimate the plant's low-temperature tolerance on a daily basis relative to its stage of phenological development.

Acclimation and the maintenance of low-temperature tolerance

Winter annual crops like winter wheat and rye over winter as seedlings that must survive prolonged exposure to low-temperature stress. In order to cope with this stress, they have evolved adaptive mechanisms that are temperature regulated.

Low-temperature acclimation, the maintenance of low-temperature tolerance, and the degree of low-temperature injury during the winter are directly related to the genetic potential of the plant and the sequence of temperature changes to which the plant is exposed. Low-temperature damage to the crown of the plant during periods of cold is the main cause of winterkill in most climates where the soil temperature falls below freezing during the winter months. Consequently, it is the soil temperature at this depth that is critical to the acclimation process and winter survival. The crown is normally located less than 5 cm (two inches) below the soil surface.

Cold acclimation is a cumulative process that can be stopped, reversed, and restarted. The acclimation process normally starts once temperatures fall below approximately 10°C. Once cold acclimation has been completed, fully acclimated winter cereals can maintain a high level of cold hardiness provided crown temperatures remain below freezing. However, acquired low-temperature tolerance is rapidly lost once acclimated winter cereals are exposed to warm crown temperatures that promote active plant growth.

When growth starts in the early fall, winter cereal plants will not survive subfreezing temperatures much better than spring cereal plants. However, winter cereals grown under cool fall temperatures will cold acclimate or "harden off". For example, the minimum survival temperature for Norstar winter wheat is normally near -3°C at the beginning of September and -19°C or lower by the end of October at Saskatoon Saskatchewan, Canada. Winter cereals normally do not realize their maximum cold hardiness potential until after the soil freezes in the late fall or early winter. In Saskatchewan, full acclimation is usually achieved by the middle to the end of November. A return to crown temperatures above 9°C in the spring accelerates plant growth and eventually results in a complete dehardening of winter wheat. Growth rate and rate of dehardening are both temperature dependent. Therefore, because frozen soils warm slowly in the spring, several weeks of warm air temperatures are required to re-establish and completely deharden winter cereal plants that have survived without winter damage.

The low temperature requirement for cold hardening is also the cue that results in vernalization, or the conversion of winter cereals to a "spring form". Fulfillment of vernalization requirements has been associated with over winter declines in low-temperature tolerance of plants maintained at temperatures in the vernalization range (between approx. 0 and 10°C, Fowler et al. 1996b). The warmer the crown temperature after vernalization, the more rapid the rate of decline in cold hardiness level. Further research has shown that any factor which delays the transition from the vegetative to reproductive stage will extend the period during which plants can maintain a high level of low-temperature tolerance. Consequently, a photoperiod requirement also becomes an important over wintering factor in climates with long periods in the fall and winter when the temperatures are in the vernalization range (Fowler et al. 2001, Mahfoozi et al. 2001a, b).

Low-temperature damage

In nature, low-temperature acclimation of a cereal plant proceeds slowly and, for the most part, at temperatures above freezing. While the low-temperature tolerance of a plant is continually adjusted in response to changing environmental conditions during the winter, death of the crown tissue will result if the soil temperature falls below the plants minimum survival temperature. Exposure of winter cereal plants to crown temperatures that are 2 to 3°C warmer than their minimum survival temperature will cause immediate damage and a reduction in cold hardiness. The low-temperature tolerance of winter cereal crowns is reduced by prolonged exposure to near lethal temperatures and, as a consequence, both temperature and exposure time play an important role in determining degree of injury (Fowler et al. 1999).

The model updates low-temperature tolerance estimates daily, thereby providing a current record of the plant's ability to tolerate low-temperature stress. Death of the plant is assumed to occur if the average daily soil temperature at crown depth falls below the daily adjusted minimum survival temperature. Simulation studies have shown that small differences in cultivar genetic potential (LT50C = temperature at which 50% of the plants are killed) translate into large differences in survival when the cumulative effects of low-temperature stress enter the critical range for over winter survival.

The model generates a new graph when any of the field values on the menu page are changed and the page is updated. The graph will display the range of dates that are currently in the data file. Two lines will appear - one in red one in blue. The red line is the minimum survival temperature or winter hardiness of the selected cultivar. The blue line is the average daily temperature at optimum crown depth for that particular series of data. Winterkill will be predicted when the two lines cross. Because the model only has access to spot soil temperatures from the sample field(s), a single winterkill event cannot be extrapolated to conclude that the cultivar has suffered winter damage in a larger geographic region. The output is only an indicator of the level of stress and the model continues monitoring crop condition throughout the winter. Each potential winterkill event is recorded and the larger the number of days with winterkill predicted the greater the likelihood that crop damage will be more widespread. The picture behind the graph reflects potential severity of the winter damage, but the number of winterkill events is a more useful indicator for comparative studies. A healthy, undamaged crop is shown until 13 or more winterkill events are predicted. At this point the picture changes to that of a field in which there has been variable winter damage (Figure 1). The picture changes to one of complete winterkill once the number of winterkill events reaches 33.


Figure 1. Fall tilled or conventional summerfallow fields have poor snow trapping capabilities. Snow either drifts into small dunes or off of the field completely. This results in variable snow cover and abrupt changes in crop winter stress levels that appear as patchy survival patterns the following spring. Areas that are green survived under snow banks (dunes) during the coldest part of the winter.

<u>Genetic Coefficients</u>

a) Low-temperature tolerance: There are large cultivar differences in the low-temperature tolerance that must be accommodated before crop models can effectively simulate the over wintering of cereals. These differences are recognized in the model through the use of genetic coefficients (LT50C) that have been field validated in western Canada (Fowler 1992, http://www.usask.ca/agriculture/plantsci/winter_cereals/Winter_wheat/CHAPT12/cvchpt12.php#date).

The model has been calibrated using a LT50C of -24°C for Norstar and the other cultivar coefficients in the variety menu have been adjusted accordingly. The general pattern of over-winter low temperature response is similar for cereal cultivars both within and among species. Although there is an overlap among species, cultivars of rye have the best low-temperature tolerance of the cereals. Cultivars of common wheat and triticale are next in line followed by durum wheat, barley, and then oat. The winter survival model also has potential application in the simulation of over wintering for a wide range of other plant species. For example, the necessary genetic coefficients (LT50C) for simulation during the establishment year can be determined from published low-temperature tolerance ratings of cultivars representing forage grass species and other wheat relatives (see Fowler et al. 1999 for a list of references). The genetic coefficients can also be modified to accommodate the effects of management practices on low-temperature gene expression.

b) Stage of development: The winter survival model assumes that both the level and duration of gene expression determine plant low-temperature tolerance. As indicated above, the level of low-temperature tolerance is determined by a coefficient that corrects for cultivar differences in cold hardiness potential. However, as explained earlier, low-temperature gene expression is down regulated once the plant enters the reproductive growth stage. Therefore, any factor that delays the transition from the vegetative to reproductive stage, such as vernalization or photoperiod requirement, can be expected to affect the expression of low-temperature genes in cereals exposed to acclimating temperatures (Fowler et al. 1996a, b, Mahfoozi et al. 2001a, b).

Under long days, spring habit cultivars enter the reproductive stage shortly after germination while winter habit cultivars have a vernalization requirement that delays this transition until the plants have experienced a period of growth at temperatures in the 0 to 10°C range. Consequently, a vernalization coefficient must be entered in order for the model to function properly. Experience indicates that the vernalization coefficient is approximately 21 for spring habit cultivars and 52 for winter habit cultivars and the model defaults have been set at these values. However, these are approximations and the user is given the opportunity to experiment with different values by simply changing the values in the vernalization coefficient box.

The model is very sensitive to changes in the vernalization coefficient. This limitation does not appear to be a critical factor in environments like western Canada where fall temperatures cool down very quickly and once the soil freezes (early November) it stays frozen until spring. However in more moderate winter climates, where fall temperatures cool down slowly and there is a long period in the fall and winter when the temperatures are in the vernalization range, the model does not hold the plant in the vegetative stage as long as would normally be expected. Research has shown that photoperiod responses can play an important role in delaying the vegetative/reproductive transition in these environments. However, we haven't yet determined the critical day lengths (night lengths) that are necessary for a photoperiod routine to be developed. At present photoperiod requirements and the effect of vernalization by photoperiod interactions can only be accommodated by changing the vernalization coefficient.

Crop Management Factors

Snow cover: Death of the winter cereal plant will occur if the soil temperature falls below the minimum survival temperature of the crown at any time during the winter. Therefore, the temperature to which plant crowns are exposed is the critical factor that determines the winter survival of cereals. The crown of the plant is normally located less than 5 cm below the soil surface and the soil has a tremendous capacity to buffer temperature change. However, a protective snow cover is usually required to prevent soil temperatures from falling below the minimum survival temperature for wheat in harsh winter climates like that of western Canadian (Fowler 1992).

Snow will drift into dunes on the field giving the plants variable protection from cold winter air temperatures. Minor variation in snow cover over a distance of just a few meters can cause large differences in soil temperatures with the result that changes in stress levels are often very abrupt. The usual consequence of variable snow cover and cold temperatures is patchy survival patterns in the spring (Figure 1). These observations also emphasize one of the limitations of the model. The model simulates plant winter hardiness based on soil temperatures that are spot measurements. However, because soil temperatures can be quite variable across a field, survival estimates generated by the model must be considered rough approximations of the average level of winter stress experienced in a region. The limited resources at Saskatoon allow us to maintain two weather stations, which we locate in winter wheat fields. Each weather station has two soil probes (P1 and P2) that are positioned several meters apart to give us a total of four different measures of soil temperature. The data available to the model includes soil temperatures at crown depth for conventional summerfallow (or fields with poor snow trapping potential = high stress environment) and standing stubble (low stress environment). The high stress locations have been identified in the menu by including the word "high" in the data file name.

The effect of small differences in soil temperature can be seen by selecting Norstar and running the model using the Saskatoon P1 and P2 95-96 data files. Patchy winterkill was observed at the Saskatoon low-stress site in the spring of 1996. The model predicted no damage at the probe 1 (P1) and six winterkill events at the probe 2 (P2) locations from December 10 to 15 in 1995 when the soil temperature was 1 to 2^{o}C warmer for probe 1 compared to probe 2 at this site.

Agronomy: Maximum opportunity for winter survival can only be achieved when optimum management practices are employed. In western Canada, risk of winterkill is minimized when properly fertilized winter cereals are seeded shallow with a no-till drill into a moist, weed-free field of standing stubble on the recommended seeding date. Management shortfalls in any of the above areas will result in a reduction in cultivar winter survival potential.

Seeding date, seeding depth and phosphorus and nitrogen fertilization have all been shown to affect winter hardiness. The impact of sub-optimal management of these factors has been determined in field trials that have experienced differential winterkill and these estimates of reduction in winter survival potential (Fowler 1992) can be applied directly to winter survival simulations by using the Management Impact Calculator. For example, by clicking on the Management Impact Calculator we find that seeding one month later than the recommended date in western Canada is expected to reduce a cultivars winter survival by 38 Field Survival Index (FSI) units compared to seeding on the optimum date. Subtracting 38 from the cultivar FSI, entering the difference in the FSI box and clicking on the = button of the FSI box we find that a one-month delay in seeding date reduces the LT50C of the cultivar of interest by 1.55^{o}C. The effect of this management deficiency on winter survival potential can then quickly be seen in the changes to the resulting graph and the estimated number of winterkill events. (Note: Clicking on the Management Impact Calculator button takes you to Table 6 in chapter 12 of the Winter Wheat Manual. By scrolling up and down you can find tables that show the FSI reductions expected for other sub-optimal management practices).

Summary

The winter survival model has been field validated for cereals over wintered at Saskatoon, Saskatchewan, Canada. It also has potential application in the simulation of low-temperature responses of a broader range of species and climates. The crop variety menu offers the choice of a wide range of winter cereal species and cultivars. The LT50C and vernalization options allow the user to expand on these choices and experiment with different values. The data files contain soil temperature records for selected years and locations that can be expanded when new data becomes available. The present files include examples from Canada (Saskatoon and Indian Head, Saskatchewan and Oak River, Manitoba) and Prague, Czech Republic. Soil temperatures for the current year are also being added as the winter progresses thereby allowing interested users to monitor the predicted condition of the present crop in the Saskatoon region. In addition, a Management Impact Calculator allows users to evaluate the effects of sub-optimal seeding date, seeding depth and phosphorus and nitrogen fertilization management on the winter hardiness of crops grown in western Canada. A large database that can be quickly and easily supplemented combined with an flexible, interactive model which complies with the known low-temperature responses of cereals creates a teaching tool that allows production risks, cause-and-effect processes, and genetic theories to be systematically investigated by users throughout the world.

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