

# Indices for Assessing Site and Winegrape Cultivar Risk for Spring Frost

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**ABSTRACT.** Spring frosts are of significant concern to growers of many fruit-bearing horticultural crops such as winegrapes. In many regions of the continental United States, winegrape crops are in danger of reduction or total loss every year. Inexperienced growers are often ignorant of the potential economic ramifications that spring frosts can incur. A new index, the frost index (FI), is proposed to aid growers in choosing sites where risk of damaging spring frost is minimized. The FI presents an improvement over current frost indices because it not only accounts for temperature but frost risk period and total number of frost events. A variation of FI for assessing cultivar risk at a specific site is also presented. The FI can be adjusted for any growing location, depending on timing of frost risk and budbreak. FI allows growers to make interpretations of frost risk potential with greater precision than current indices.

**KEYWORDS.** Budbreak, continentality, economic risk, fruit crops, grape

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This manuscript is approved for publication by the director of the Oklahoma Agricultural Experiment Station. The assistance and comments provided by Dan Chapman, University of Arkansas, Al Sutherland, Oklahoma Mesonet, David Lockwood, University of Tennessee, Richard Heerema, New Mexico State University, and Michael Smith, Oklahoma State University are appreciated.

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International Journal of Fruit Science, Vol. 7(4) 2007

Available online at <http://ijfs.haworthpress.com>

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doi:10.1080/15538360802003415

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## INTRODUCTION

Spring frosts are one of the greatest concerns for growers of fruit-bearing horticultural crops like winegrapes (*Vitis* spp.). Many commercial winegrape cultivars break bud before the normal “frost-free” date and are therefore at considerable risk, especially in the southern region of the United States where crops flower during frost prone periods (Himelrick and Galletta, 1990; Vega et al., 1994). Many new growers do not understand the inherent risk of potential crop reduction or loss due to spring frost or freeze conditions when growing winegrapes. Extension scientists are often assigned the responsibility of adequately explaining this risk through cultivar budbreak dates, site frost-free dates, and other genotypic and environmental data. Creation of a single numerical index from existing climate data that reflects crop loss potential from spring frost events would benefit growers looking for sites and cultivars that minimize their risk in an easily understandable quantitative value.

There have been few attempts to develop a spring frost index, and most of those have focused on grapes. Gladstones (2000) introduced a spring frost index (SFI) based on the range between the monthly average mean temperature and the average lowest minimum for the spring months in which budbreak and frost potential were concomitant. April and May data were used for the northern hemisphere and October and November data for the southern hemisphere to calculate the SFI. During spring, the concern is occasional low-temperature events, which Gladstones stated would be reflected in the averages of the monthly lowest minimum temperatures. Since damage would be greater when average temperatures are higher, due to presumed earlier budbreak, the difference between the two temperatures would be representative of a location’s continentality and spring frost risk. Wolf and Boyer (2003) modified Gladstones’ original equation to use the average monthly mean temperature minus the average monthly mean minimum temperature instead of the average monthly lowest minimum temperature. They also presented temperatures in Fahrenheit rather than Celsius. Rossi et al. (2002) created a frost index based solely on mean minimum temperature and then used regression analysis to map regions of Italy and their relative susceptibility to frost injury for fruit orchards.

Other work has addressed spring frosts in the context of site or cultivar selection but did not necessarily propose an index. Trought et al. (1999) focused on determining frost risk for cultivars at different locations within New Zealand based on predictive phenology stage (Moncur et al., 1989)

and frost probabilities. This approach was also used by Poling et al. (2007) for sites in North Carolina, with slight variations by using long-term weather data and performing an investment analysis. A more comprehensive attempt to characterize vineyard site selection was done by Kurtural et al. (2006) using geographical information systems (GIS). The research done by Kurtural et al. (2006) to characterize appropriate sites for grapes are useful in the state or region for which they are produced, but growers in areas where grapes do not comprise large acreages may find this type of data collection and analysis daunting. So, although highly useful, the practicality of this approach is limited for growers who have limited or no familiarity with GIS technologies, statistical analysis, and data mining.

A new index that incorporates events in addition to temperature is proposed that makes a more practical representation of actual site frost risk than either SFI currently present. This new index can be calculated easily by growers who have access to daily weather data and budbreak data. Often short-term data are readily obtainable at online weather sites and long-term data are available through state climatologists. Budbreak data can be obtained from extension or research scientists in the state of interest. The new index can also be adapted to compare cultivars with each other as well as to the site to facilitate selection of cultivars where timing of budbreak is directly related to actual frost and freeze events. This knowledge will play an important role in reducing economic loss risk by growers who desire to produce winegrapes in areas where spring frost risk has been previously unexamined.

## ***MATERIALS AND METHODS***

Weather data for the months of March through May were obtained from the Oklahoma Climatological Survey from 100+ years of data for two locations in Oklahoma (Stillwater and Chandler). Data were also provided from the University of Arkansas Fruit Substation, Clarksville, AR (D. Chapman, personal communication) for 1994–2007. Data from other locations were obtained from the National Oceanic & Atmospheric Administration (NOAA) Web site (Fayetteville and Fort Smith, AR), the New Mexico regional climate center, the Oklahoma Mesonet system (Perkins, OK), and Weather Underground ([www.wunderground.com](http://www.wunderground.com)) (NC, TN, and TX).

The Gladstones (2000) spring frost index (°C) was calculated as:

$$\text{SFIg} = [(\text{ATmax} + \text{ATmin}) / 2] - \text{Tlow},$$

where  $AT_{max}$  = average monthly maximum temperature,  $AT_{min}$  = average monthly minimum temperature, and  $T_{low}$  = lowest monthly temperature (for April).

The modification of SFIg to incorporate cultivar-specific information was calculated as:

$$CSFIg = [(AT_{maxbb} + AT_{minbb}) / 2] - T_{lowbb},$$

where  $AT_{maxbb}$  = average maximum temperature from budbreak to 30 Apr.,  $AT_{minbb}$  = average minimum temperature from budbreak to 30 Apr., and  $T_{lowbb}$  = lowest monthly temperature from budbreak to 30 Apr.

The Wolf and Boyer (2003) modification of SFI ( $^{\circ}F$ ) was calculated as:

$$SFIw = [(AT_{max} + AT_{min}) / 2] - AT_{min},$$

where  $AT_{max}$  = average monthly maximum temperature and  $AT_{min}$  = average monthly minimum temperature.

The modification of SFIw to incorporate cultivar-specific information was calculated as:

$$CSFIw = [(AT_{maxbb} + AT_{minbb}) / 2] - AT_{minbb},$$

where  $AT_{maxbb}$  = average maximum temperature from budbreak to 30 Apr. and  $AT_{minbb}$  = average minimum temperature from budbreak to 30 Apr.

The proposed frost index ( $^{\circ}C$ ) for site was calculated as:

$$FI = ([\{AT_{max} + AT_{min}\} / 2] - T) \times (1 - [LFD/30]),$$

where  $AT_{max}$  = average monthly maximum temperature,  $AT_{min}$  = average monthly minimum temperature,  $T$  = sum of difference of absolute temperatures below  $0^{\circ}C$ , and  $LFD$  = last frost day of year during month of interest (in this case, April when the low temperature for the date is below  $0^{\circ}C$ . If  $LFD$  is before 1 April then  $LFD = 0$ ). For example in 2005 at Stillwater, the average monthly maximum temperature for April was  $23^{\circ}C$ , the average monthly minimum temperature for April was  $7.7^{\circ}C$ , the total absolute degrees below  $0^{\circ}C$  for the month was 1, and the last frost day was 25 April, thus:

$$FI = ([\{23 + 7.7\} / 2] - 1) \times (1 - [25/30])$$

$$FI = 14.4 \times 0.17$$

$$FI = 2.4$$

The proposed frost index ( $^{\circ}\text{C}$ ) for cultivar on a site was calculated as:

$$\text{CFI} = ([\{AT_{\text{maxbb}} + AT_{\text{minbb}}\} / 2] - T_{\text{bb}}) \times (1 - (F_{\text{bb}} / L_{\text{bb}})),$$

where  $AT_{\text{maxbb}}$  = average maximum temperature from budbreak to 30 April,  $AT_{\text{minbb}}$  = average monthly minimum temperature from budbreak to 30 April,  $T_{\text{bb}}$  = sum of absolute temperatures below  $0^{\circ}\text{C}$  from budbreak to 30 April,  $F_{\text{bb}}$  = total number of days from budbreak to last frost day (if last frost precedes budbreak, then  $F_{\text{bb}} = 0$ ), and  $L_{\text{bb}}$  = total days from budbreak to 30 April. For example, ‘Chardonnay’ in 2007 at Perkins, OK, the equation follows the FI illustration presented above with the modifications described for the CFI, thus:

$$\text{CFI} = (14.8 - 6) \times (1 - [20/42])$$

$$\text{CFI} = 8.8 \times .52$$

$$\text{CFI} = 4.6$$

The Oklahoma State University Cimarron Valley Experiment Station is located at Perkins, OK, where an experimental vineyard is planted with the winegrape cultivars presented in Table 4. This location was chosen because of the accumulation of weather and phenological data available.

All indices were calculated for April (following the example of Wolf and Boyer, 2003), as April is typically the month in which budbreak occurs and frost risk is highest for the south central United States. The FI can be adjusted for any growing location, depending on timing of frost risk and budbreak. In more northern locations, budbreak may not begin until late April and frost risk may run into May. In this situation one might choose April 20 through May 20 as the frost-risk period. Locations farther south may experience rare April frosts and therefore early March to early April may be the frost period of interest.

Frosts in May are rare for most of the locations analyzed. The base temperature of  $0^{\circ}\text{C}$  was used in calculating the FI because temperatures below that threshold can cause damage, especially to tender vegetation (Peacock, 1998; Vega et al., 1994). Instances of very late frost (i.e., 30 April or later) could result in a FI of 0. Extreme cold could also result in a very low FI, in some cases negative numbers. Often negative values

occurred in highly abnormal situations; therefore, values less than 0 had little meaning, as anything less than 7.5 is in the very high-risk category, and were defaulted to 0. Pearson product-moment correlations were calculated with JMP (SAS Inst., Cary, NC). Regression analysis was performed using the Fit Model procedure in JMP.

## RESULTS AND DISCUSSION

Gladstones (2000) did not propose a definition of what values fell into the high, moderate, and low categories, but Wolf and Boyer (2003) suggested the relative ranges outlined in Table 1 for Virginia based on Fahrenheit temperatures. The interpretations of values by Gladstones (2000) generally were in the range of those described by Wolf and Boyer (2003), but for Celsius temperatures. Interpretations of frost risk for FI presented in Table 1 were based on regression analysis (data not shown) to determine what the FI would be at the number of frosts observed from 0 (considered low) through 3 (considered high) and averaging the values obtained for total frost/freeze events and average absolute frost/freeze temperature for both locations in Table 1 (Chandler and Stillwater, OK).

When SFIg, SFIw, and FI were calculated for two locations in Oklahoma (Chandler and Stillwater) with more than 100 years of climate data,

TABLE 1. Interpretations for spring frost index (SFI) (Gladstones, 2000 [ $^{\circ}$ C]; Wolf and Boyer, 2003 [ $^{\circ}$ F]) and frost index (FI) ( $^{\circ}$ C)

Index value	Relative risk
<i>SFI</i>	
< 11 <sup>z</sup>	Low (L)
11–13	Moderate (M)
> 13	High (H)
<i>FI</i>	
>15.0	Low (L)
12.5–15.0	Low to Moderate (L-M)
10.0–12.5	Moderate to High (M-H)
7.5–10.0	High (H)
< 7.5	Very High (VH)

<sup>z</sup>The index values for both Gladstones (2000) and Wolf and Boyer (2003). Gladstones interpretation is for degrees Celsius, whereas Wolf and Boyer is for degrees Fahrenheit.

TABLE 2. Comparison of spring frost indices at two locations in Oklahoma (Chandler and Stillwater) based on correlation to average total frost/freeze events (TE), average date of last frost (LD), and average absolute degrees below 0 °C (32°F) for frost/freeze events (FZ)

Index	Variable	<i>r</i>	P	Years of data	Index value	Risk
<i>Chandler</i>						
SFIg <sup>z</sup>	TE	0.5073	0.0001	102	16.5	H
	LD	0.3553	0.0002			
	FZ	0.7750	0.0001			
SFIw <sup>y</sup>	TE	0.0793	0.4282		12.2	M
	LD	0.0012	0.9906			
	FZ	0.0289	0.7729			
FI <sup>x</sup>	TE	-0.7970	0.0001		12.7	L-M
	LD	-0.7887	0.0001			
	FZ	-0.6118	0.0001			
<i>Stillwater</i>						
SFIg	TE	0.4970	0.0001	111	16.8	H
	LD	0.3335	0.0003			
	FZ	0.7459	0.0001			
SFIw	TE	0.2342	0.0133		12.4	M
	LD	0.2852	0.0024			
	FZ	0.1992	0.0360			
FI	TE	-0.8382	0.0001		10.6	M-H
	LD	-0.8240	0.0001			
	FZ	-0.6730	0.0001			

<sup>z</sup>Spring frost index, Gladstones (2000).

<sup>y</sup>Spring frost index, Wolf and Boyer (2003).

<sup>x</sup>Frost index.

correlation analysis was performed to determine if they had any linear relation to average last date of frost/freeze (LD), average absolute frost/freeze temperature (FZ), and average total frost/freeze events (TE) (Table 2). The SFIg was significantly correlated to TE, LD, and FZ at Chandler and Stillwater, but correlation coefficients were not high for any variable, especially LD. The FI was strongly correlated with the three dependent variables at both locations (Table 2). The SFIg at Chandler indicated high risk whereas FI was in the low to moderate category. The SFIg value at Stillwater was slightly greater than Chandler and FI designates the risk as moderate to high. The SFIw was not significantly correlated for the variables at Chandler and was significant but weakly correlated for the variables at Stillwater.

Gladstones (2000) indicated that locations with lower SFI values were at less risk than those with higher values because a lower SFI would be indicative of less continentality, lower average temperatures, and higher minimum temperatures, thus leading to later budbreak and avoidance of frosts. However, Trought et al. (1999) stated that years with later budbreak also often have later frosts and therefore delayed budbreak did not necessarily equate to less frost risk; thus, frost risk is also associated with low continentality, because the period of frost risk is presumably longer (Gladstones, 1992). Both the SFIg and SFIw are essentially measures of continentality, but both high and low continentality represent some level of frost risk (Gladstones, 1992, 2000). Therefore, the real measure of potential frost injury primarily depends on two separate factors, in addition to temperature, that coincide: the timing of the frost event and the developmental stage of the plant (Trought et al., 1999). For all of the indices for site, the developmental stage of the plant is assumed as starting budbreak on or about 1 April. The timing of frost events is not addressed in SFIg and SFIw. For both of these indices, a frost on 1 April is given the same importance as a frost on 30 April. The FI incorporates frost timing, by assuming that later frosts will be more damaging than earlier frosts due to advanced plant phenology.

The SFIg interpretation for all locations in Table 3 was in the high-risk category. For SFIw, 10 of the 15 locations were in the moderate category, with 4 of 15 in the high-risk category (Artesia, Clovis, and Las Cruces, NM and Lubbock, TX), and only 1 location in the low category (Crossville, TN). The FI placed five locations in the very high or high category (Fayetteville, AR, Artesia and Clovis, NM, Asheville, NC, and Crossville, TN), eight in the moderate categories, and two in the low category (Abilene and Wichita Falls, TX). Some of the locations vary greatly when the indices were compared. The SFIg and FI were in general agreement on 9 of the 15 locations but disagreed strongly on the remainder. The SFIw and FI gave similar predictions on 9 of the 15 locations but were very different for Fayetteville, AR, Las Cruces, NM, Asheville, NC, Crossville, TN, Abilene, TX, and Wichita Falls, TX.

When sites are ranked from lowest risk to highest risk within a state, the inconsistencies of the SFI indices in measuring frost risk become readily apparent. For Arkansas, all indices rank Fayetteville as the riskiest location. The SFIg has Clarksville as lowest, whereas FI has Fort Smith as lowest. The SFIw predicts Fayetteville and Fort Smith as having the same frost risk, but Fort Smith has fewer events, less severe cold events, and an earlier average last frost. The FI ranks Clovis, NM, as having the highest

TABLE 3. Selected locations outside of Oklahoma where April is the month of frost risk with at least 10 years of climate data for calculation of Gladstones' spring frost index (SFIg), Wolf and Boyer's spring frost index (SFIw), the proposed frost index (FI), average frost/freeze events (TE), average date of last frost (LD), and average absolute degrees below 0 °C (32 °F) for frost/freeze events (FZ)

State	Site	SFIg	SFIw	FI	TE	LD	FZ
Arkansas	Clarksville <sup>z</sup>	14.9	11.0	13.6	0.5	3–27	2.1
	Fayetteville <sup>y</sup>	17.1	12.2	5.9	2.3	4–13	2.9
	Fort Smith <sup>x</sup>	15.8	12.2	14.6	0.5	3–23	0.7
New Mexico <sup>w</sup>	Artesia	18.1	18.4	10.3	2.2	4–6	2.0
	Clovis	16.6	16.0	3.8	3.9	4–15	4.3
	Las Cruces	17.8	18.8	13.0	0.9	3–30	1.0
North Carolina <sup>y</sup>	Asheville	15.1	12.1	7.2	1.7	4–8	2.9
	Charlotte	16.1	12.4	11.9	0.8	3–26	1.1
	Greensboro	15.3	11.5	11.3	0.7	4–2	1.5
Tennessee <sup>y</sup>	Crossville	14.4	10.3	8.2	1.9	4–6	1.6
	Jackson	16.7	11.5	11.5	1.2	4–4	1.8
	Nashville	15.0	11.0	13.7	0.5	3–26	1.1
Texas <sup>y</sup>	Abilene	16.4	12.6	16.0	0.4	3–25	1.4
	Lubbock	16.3	14.1	11.4	1.2	4–3	1.5
	Wichita Falls	15.6	12.6	16.0	0.3	3–19	0.9

<sup>z</sup>Data from 1994–2007 (University of Arkansas Fruit Substation).

<sup>y</sup>Data from 1997–2007 (National Oceanic & Atmospheric Administration).

<sup>x</sup>Data from 1995–2007 (National Oceanic & Atmospheric Administration).

<sup>w</sup>Data from 1985–2007 (New Mexico Climate Center).

<sup>v</sup>Data from 1997–1999, 2001–2007 (Weather Underground).

risk and Las Cruces the least, but SFIg and SFIw have Clovis as the least risky location. Clovis has the latest average frost date, the most cold events, and most severe cold events of the three sites in New Mexico. The SFIg has Artesia and SFIw has Las Cruces at most risk. In North Carolina, both SFIg and SFIw have Charlotte as the riskiest site, but FI has it as the least risky. The FI has Asheville as the riskiest. The SFIg has Asheville as least risky and SFIw has Greensboro as least risky. For Tennessee, SFIg and SFIw concur on all locations. The FI has Crossville as most at-risk and Nashville as least. The SFIw and FI agree on all locations in Texas in terms of rank. The SFIg has Abilene at greater risk than Lubbock; although, according to TE, LD, and FZ, Lubbock is obviously a more at-risk location than Abilene. By ranking each site within state for TE, LD,

and FZ and averaging those values, FI rankings are in agreement at every location.

The SFIw is an index for frost potential, but in many years that potential is never realized and in those instances the results may give a grower a false sense of the risk that actually existed at a particular site. Also, a singular damaging frost or freeze event is not likely to influence the average minimum temperatures for the month to a great extent, thus rendering the SFIw a poor indicator of frost risk. The SFIw does not work effectively in areas where warm daytime temperatures in the spring are coupled with nighttime temperatures that remain relatively low. The location has high daytime temperatures and cooler nighttime temperatures, but not near freezing. This situation leads to a high SFIw. The potential for injury, if a frost was to occur, would be significant; yet, in reality the likelihood that a frost would occur is low.

Frost indices can also be used for determination of specific cultivar frost risk if budbreak date is known or can be predicted. In Table 4, five years of grape budbreak data were used to assess potential frost risk. Only 2007 had any significant crop loss due to an April freeze at Perkins, although a frost occurred after budbreak in 2003. Discrepancies existed between SFIg and FI. Both indices concurred on most cultivars, except 'Malbec'. In 2003, early April frosts occurred, and 'Malbec' reached budbreak on 9 April, the last frost day of the year. Generally, the Perkins location is not at high risk for spring frosts, but 'Cabernet Franc', 'Chardonnay', 'Pinot Gris', 'Sangiovese', and 'Shiraz' were all at higher risk than the site average mainly due to their earlier budbreak. One very noticeable instance in which SFIw does not adequately describe frost risk was with 'Chardonnay'. The five-year average was 11.0, indicating low risk, but 'Chardonnay' routinely breaks bud before the last frost date. For the nine cultivars in Table 4, the cutoff budbreak date for being at less risk than the site was about 5 April. Budbreak earlier than that date was at more frost risk than the site average. One could use average budbreak or budbreak modeling (Moncur et al., 1989; Poling et al., 2007) to determine cultivar risk for more years.

For 2003, the SFI indices work because frosts occurred, although they caused little or no damage. No frosts occurred from 2004 to 2006 during April, yet the SFI indices for 2006 were in the high category. This was followed by 2007, when significant damage from freeze occurred. The SFIg at Perkins was 17.2, the high category, yet the SFIg will always be high according to the interpretation given by Gladstones (2000), regardless of budbreak date, due to the continental climate of Oklahoma. More troublesome is the SFIw, which was in the low category for 2007. The FI reflects a more appro-

TABLE 4. Frost index comparison of *V. vinifera* winegrape cultivars and site (Perkins, Okla.) by year and average

Cultivar	Index	2003	2004	2005	2006	2007	Avg.
Cabernet Franc	CSFlg <sup>z</sup>	18.5	14.5	15.9	18.5	18.8	17.2
	CSFlw <sup>z</sup>	13.1	10.4	11.4	13.1	9.2	11.4
	CFI <sup>z</sup>	12.0	15.7	16.0	19.2	4.6	13.5
Cabernet Sauvignon	CSFlg	11.5	16.1	15.5	18.6	17.5	15.8
	CSFlw	13.0	10.3	12.1	12.9	10.2	11.7
	CFI	18.3	17.3	15.6	19.3	5.0	15.1
Chardonnay	CSFlg	18.5	14.1	15.9	19.6	18.8	17.4
	CSFlw	12.5	9.5	11.9	11.9	9.3	11.0
	CFI	9.5	15.3	16.0	15.8	4.6	12.2
Malbec	CSFlg	19.6	14.8	15.7	18.6	17.7	17.3
	CSFlw	13.5	9.9	11.4	12.9	9.9	11.5
	CFI	14.6	16.0	15.8	19.3	5.2	14.2
Petit Verdot	CSFlg	11.5	14.8	15.7	18.6	17.7	15.7
	CSFlw	13.1	9.9	11.4	12.9	9.9	11.4
	CFI	18.3	16.0	15.8	19.3	5.2	14.9
Pinot Gris	CSFlg	18.5	14.9	15.9	18.5	18.2	17.2
	CSFlw	13.1	9.8	11.4	13.1	9.5	11.4
	CFI	12.0	16.1	16.0	19.2	4.8	13.6
Ruby Cabernet	CSFlg	11.5	14.9	15.8	18.5	17.7	15.7
	CSFlw	12.5	9.9	11.7	13.1	9.9	11.4
	CFI	18.3	16.1	15.9	19.2	5.2	14.9
Sangiovese	CSFlg	18.4	14.4	16.1	18.5	18.5	17.2
	CSFlw	12.9	10.7	11.5	13.2	9.5	11.6
	CFI	12.0	15.6	16.2	19.2	4.7	13.5
Shiraz	CSFlg	18.1	14.8	15.9	18.5	18.1	17.1
	CSFlw	13.0	9.9	11.4	13.1	9.6	11.4
	CFI	10.2	16.1	16.0	19.2	4.8	13.3
Site							
Perkins	SFlg <sup>y</sup>	18.7	14.5	16.0	18.6	17.2	17.0
	SFlw <sup>y</sup>	12.4	10.8	11.6	13.3	10.8	11.8
	FI <sup>y</sup>	13.7	15.6	16.0	19.2	5.3	14.0

<sup>z</sup>CSFlg = cultivar spring frost index (Gladstones); CSFlw = cultivar spring frost index (Wolf and Boyer); CFI = cultivar frost index.

<sup>y</sup>SFlg = spring frost index (Gladstones); SFlw = spring frost index (Wolf and Boyer); FI = frost index.

ropriate representation of the risk for damaging spring frost because not only does the FI take into account both maximum and minimum temperatures by using the average mean temperature but it also factors in the duration of frost, as well as the severity of the frost or freeze events.

Of course an index is only as good as the data available. It is only intended for macroclimatic interpretations around sites where the climate data exists. Mesoclimates can differ from weather stations due to factors such as elevation, slope, and aspect can vary widely in short distances (Smart and Dry, 1980). Caution should be taken when interpreting any index; however, the FI will allow growers to make interpretations of risk based on a year-to-year basis in the short-term, as well as averages over the longer term, and determine their risk threshold with greater precision than SFI<sub>g</sub> or SFI<sub>w</sub>.

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