A Comparison of Instruments and Contract Services Used to Calculate Degree-days

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SUMMARY. Various instruments and contract services can be used to calculate degree-days. This study compared instruments and services to the Wescor Biophenometer, an instrument used by cooperators of the Southeast Pennsylvania IPM Research Group (SE PA IPM RG) throughout Delaware and southeastern Pennsylvania for 10 years. Instruments evaluated in the study were the Wescor Biophenometer Datalogger, Avatel HarvestGuard, Avatel Datascribe Junior, Davis Weather Monitor II, Accu-Trax, and the HOBO H8 Pro Temperature Data Logger. The services were SkyBit and national weather data. Different combinations of instruments and services were used at three locations in Pennsylvania and four locations in Delaware over a 2-year period. We checked the degree-day accumulation of each instrument and service weekly and made statistical comparisons among the instruments and services at each site. To further construct a comparison of the instruments, we noted distinctive qualities of each instrument, interviewed the manufacturers, and received feedback from SE PA IPM RG members who used the instruments. We evaluated the instruments' algorithms, durability, cost, temperature sampling interval, ease of use, time input required by the user, and other distinctive factors. Statistically, there were no significant differences in degree-day accumulations between the Biophenometer, HarvestGuard, Datascribe, Weather Monitor II, Skybit, or weather service data. However, cost and time required to access/interpret data and personal preference should be major considerations in choosing an instrument or service to measure degree-days.

Insects and other arthropods are dependent on temperature for development. For an insect to complete a certain physiological process, sufficient heat accumulation is necessary (Clark and Kowalsick, 1993). Degree-days measure accumulated heat units. One degree-day is equal to one heat unit. A degree-day is obtained when the temperature remains one degree above a low threshold for a period of 24 hours. The standard base temperatures used are 32, 40, 43, 47, and 50 °F (0.0, 4.4, 6.1, 8.3, and 10.0 °C). For ornamental pest development, a base of 50 °F is frequently used because development is limited

below this temperature (Barton et al., 2000).

Degree-days are useful in pest management programs (Caron, 1999; Higley et al., 1986; Mussey and Potter, 1997). Degree-days are considered a more accurate predictor of arthropod development compared to traditional calendar date, since temperature varies from year to year (Raupp et al., 1992). Using a pest's temperature-driven rate of development can provide more accurate timing of control measures (Lehman, 1992), such as optimizing pesticide applications by targeting the most susceptible life stage of a pest (Ascerno, 1991; Raupp et al., 1992).

In one survey, after a 2-year period of receiving a newsletter containing degree-day information, 28% of the subscribers reported a reduction in pesticide use (Suchanic and Vorodi, 1993), and this increased to 41% after an 8-year period (Hoover, 2002).

Historically, degree-days were used more for predicting plant development rather than arthropod development (Wang, 1960). Much of the existing arthropod data (insects and mites) is for agricultural pests (e.g., Meyer and Peterson, 1998; Sparks, 1995; Tio et al., 2001) and insects used for biological control (e.g., Perdakis and Lykouressis, 2002; Rodriguez-Saona and Miller, 1999; Royer et al., 2001). Less data exist for ornamental pest species. Mussey and Potter (1997) present one of the most extensive summaries of pest data for ornamental pests.

The Southeast Pennsylvania Integrated Pest Management Research Group (SE PA IPM RG) is a collaboration of government and industry cooperators in northern Delaware and southeastern Pennsylvania. In 2001, 23 cooperator sites actively contributed to the group. Over the past 11 years, the SE PA IPM RG has accumulated degree-day data for over 100 ornamental insect pests (Suchanic et al., 2000).

There are various mathematical models used to calculate degree-days (Higley et al., 1986; Pruess, 1983; Wang, 1960; Worner, 1992). These models have been incorporated into commercially available instruments and contract services that may be used to determine and access degree-days for the current growing season. The SE PA IPM RG uses the Wescor Biophenometer Datalogger (Wescor, Inc., Logan, Utah) to calculate and accumulate degree-days.

In this study, we compared the degree-day accumulation of seven instruments and services, using a base of 50 °F, to the Biophenometer. We also compared how the instruments and services varied in their algorithms, cost, durability, functions, and ease of use.

Materials and methods

This study used seven total cooperator sites during 2000 and 2001. At each site, the degree-day instruments were located in a weather shelter. Three of the cooperator sites were located in southeastern Pennsylvania and four were located in Delaware's

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three counties. The five cooperator sites in 2000 were: the University of Delaware, Newark, New Castle County, Del. (site 1); Keystone Tree Experts, Doylestown, Bucks County, Pa. (site 2); Walter's Nursery, Point Pleasant, Bucks County, Pa. (site 3); Rehoboth Beach Country Club, Rehoboth Beach, Sussex County, Del. (site 4); and the University of Delaware Division of Facilities Management, Dover, Kent County, Del. (site 5). In 2001, instruments were added at the University of Delaware Research and Education Center, Georgetown, Sussex County, Del. (site 6) and the instruments at site 3 were moved to a new site—Longwood Gardens, Longwood, Chester County, Pa.

The instruments used in this study were the Wescor Biophenometer Datalogger, Avatel HarvestGuard (Elucit, Inc., Mendocino, Calif.), Avatel Datascribe Junior (Elucit, Inc.), Davis Weather Monitor II (Davis Instruments, Hayward, Calif.), Accu-Trax (Sensatronics, Bow, N.H.), and HOBO H8 Pro Temperature Data Logger (Onset Computer Corporation, Bourne, Mass.). The two contract services were SkyBit (SkyBit, Inc., Bellefonte, Calif.) and national weather data. Table 1 lists the instruments and services located at each site during the 2-year study.

The SE PA IPM RG initiated degree-day accumulations starting on 1 Mar., as did we in most cases. In 2000, the Datascribe, HarvestGuard, and Weather Monitor at site 1 were not started until 27 June 2000. However, in order to compare the three instru-

ments, instead of starting degree-day accumulation from zero, the degree-days were set at the 27 June 2000 total of the Wescor Biophenometer. During 2000, data from all the instruments and services were gathered weekly through 26 Sept. 2000.

In 2001, all instruments were turned on 1 Mar. 2001, except for the Accu-Trax at site 1, which was turned on 4 Apr. 2001 and calibrated to the Wescor Biophenometer's degree-day total. Readings were taken every week through 6 Aug. 2001.

All data were sorted by site and year. The Weather Monitor IIs at sites 1 and 2, the Accu-Trax at site 1, the HarvestGuard at site 2, and the HOBO H8 Pro Temperature Data Loggers at sites 1 and 3 were not analyzed statistically. The Weather Monitor IIs used a higher base temperature than the other instruments and services (Table 2), the Accu-Trax and HarvestGuard malfunctioned, and we did not develop a useful method to convert the temperature data from the HOBO Data Loggers into degree-days. The data for the other instruments and services were analyzed using SAS (version 8; SAS Institute, Cary, N.C.). We were interested in determining if degree-days varied significantly between instruments and services. Knowing that degree-days would vary between years due to temperature variation and between sites because of geographic separation, we blocked the data by site and year to determine if degree-days varied significantly among instruments at a particular location. This yielded 11 groups and within group variation was

tested using Levine's test ($P = 0.05$).

To further construct an objective and subjective comparison of the instruments, we noted distinctive qualities of each instrument, interviewed the manufacturers, and interviewed four members of the SE PA IPM RG who used the instruments. Our comparisons focused on the instruments' algorithms, durability, cost, temperature sampling interval, ease of use, time input required by the user, and other distinctive features. Based on our observations, and the information provided by the SE PA IPM RG members, we developed a rating scale, from one to five, to rate the durability and ease of use. Higher numbers indicate better durability or ease of use. Due to the low number of people who used these instruments, a consensus, rather than an average, was agreed upon for the ratings reflected in Table 3. Time input required by the user was rated as minimal, moderate, or extensive based on our observations and the SE PA IPM RG members' comments.

Results and discussion

From 2000 and 2001, we obtained over 1000 degree-day readings from 17 total instruments and services over a 53-week time-period. Sites that lacked data for one or more instruments in any given week were not used for statistical analysis. Thirty-eight weeks and 665 readings were used in the final analysis. Levine's test for homogeneity of variance yielded $P > 0.6337$ for each of the 11 comparisons. Thus, we failed to find a significant difference among the instruments and services. For pest management predictions, Higley et al. (1986) suggested that the accuracy of the data may only need to be within 10% to 15% of the actual degree-days required for insect development. Testing the data obtained by these instruments with known degree-day development data for insect species was beyond the scope of this project, but the year-end degree-day totals only varied between instruments by more than 15% in one case. In 2001 at site 2, the Biophenometer and Datascribe varied by 18%.

Other factors, such as cost, time required to access and interpret the data, and personal preference, were also evaluated. Tables 2 and 3 show objective and subjective comparisons constructed through our fieldwork and interviews with manufacturers and pro-

Table 1. Degree-day instruments and services used in a comparative study during 2000-01 and the six sites they were located at in Delaware and southeastern Pennsylvania.

Instrument	Location ^a					
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Biophenometer	x	x	x	x	x	x ^y
HarvestGuard	x	x	x			
Datascribe	x	x				
Weather	x					
Weather Monitor II	x ^x	x				
SkyBit	x	x	x	x	x	x ^y
Accu-Trax	x ^y					
HOBO Pro Data Logger	x ^y		x ^y			

^aSite 1 = University of Delaware, Newark, New Castle County, Del.; Site 2 = Keystone Tree Experts, Doylestown, Bucks County, Pa.; Site 3 = Walter's Nursery, Point Pleasant, Bucks County, Pa., during 2000 and Longwood Gardens, Longwood, Chester County, Pa., during 2001; Site 4 = Rehoboth Beach Country Club, Rehoboth Beach, Sussex County, Del.; Site 5 = University of Delaware Division of Facilities Management, Dover, Kent County, Del.; and Site 6 = University of Delaware Research and Education Center, Georgetown, Sussex County, Del.

^xDuring 2001 only.

^yDuring 2000 only.

Table 2. The mathematical formulas incorporated in instruments and contract services that measure degree-days and degree-day measurement specifics.

Instrument	Formula for degree-day calculation	Method/measurement interval	Low threshold for degree-day calculation (°F) ^z	Ability to select multiple thresholds
Wescor Biophenometer	Average temperature for the day – lower threshold	Automatic/10 min	50	Yes
Avatel HarvestGuard	1. The current temperature or upper threshold (whichever is lower) – lower threshold × 15 min 2. The result of step one is added to the internal degree-minutes and divided by 1440 min/d ^z	Automatic/15 min	50	Yes
Avatel Datascribe Jr.	Same as HarvestGuard	Automatic/15 min	50	Yes
SkyBit	(Actual temperature – lower threshold) ÷ 24 h	Automatic/1 h	50	Yes
Davis Weather Monitor II	Unknown	Automatic/15 min	65	No
Weather data	[(Maximum temperature + minimum temperature) ÷ 2] – lower threshold –or– {[6 (maximum temperature – lower threshold)] ÷ (maximum temperature – minimum temperature)} ÷ 12 h ^a	Manual/24 h	50	Yes
HOBO H8 Pro Temperature Data Logger	Measures temperature, not degree-days	Automatic/Adjustable	None	No
Accu-Trax	Unknown	Automatic/Unknown	50 (10)	Unknown

^zThis indicates the lower threshold used for the degree-day measurements in this study. Only the Davis Weather Monitor II has a set lower threshold that cannot be altered [(°F – 32) ÷ 1.8 = °C].

^aOther HarvestGuard models are available that use a different calculation equation.

^bWeather data gives temperature data. To calculate degree-days, we used the first equation, the averaging method, when the high and low daily temperatures fell within the high and low thresholds. We used the second equation, the single triangulation method, when the low temperature fell below the low threshold. Other formulas can also be used to calculate degree-days from weather data.

Table 3. Features of instruments and contract services that were used at six locations during 2000–01 to measure degree-days; obtained from fieldwork, interviews with the manufacturers, and interviews with cooperators who used the instruments.

Instrument	Manufacturer	Cost	Additional hardware requirements	Ease of use rating (1–5 scale) ^z	User time required	Durability rating (1–5 scale) ^y
Wescor Biophenometer	Wescor, Inc., Logan, Utah	\$700 and \$100–150 for bi-yearly recalibration	None	4	Minimal after initial set-up	5
Avatel HarvestGuard	Elucit, Inc., Mendocino, Calif.	\$200	None	5	Minimal	4
Avatel Datascribe Jr.	Elucit, Inc.	\$129	Computer for downloading data	3	Moderate	4
SkyBit	SkyBit, Inc., Bellefonte, Calif.	\$50/month and \$5/month for degree-day data	E-mail access	3	Minimal	5
Davis Weather Monitor II	Davis Instruments, Hayward, Calif.	\$395 and \$165 for software	Constant power supply and computer hook-up	2	Moderate	4
Weather data	National Weather Service, Silver Spring, Md.	\$0	Formulas and calculator to convert data to degree-days	3	Extensive	Not applicable
HOBO H8 Pro Temperature Data Logger	Onset Computer Corp., Bourne, Mass.	\$50	Like weather data plus a computer for downloading data	2	Extensive	4
Accu-Trax	Sensatronics, Bow, N.H.	\$200	None	4	Minimal	1

^zScale from 1 to 5 with 1 = difficult and 5 = easy.

^yScale from 1 to 5 with 1 = unreliable and 5 = very durable.

fessionals who used the instruments.

The Wescor Biophenometer was the original instrument chosen by the SE PA IPM RG to calculate degree-days. However, our goal was to evaluate other options due to the instrument's expense (Table 3). The Biophenometer calculates cumulative degree-days and the degree-day data are displayed on the instrument by pushing a button. The instrument needs to be checked more frequently if data for a smaller time scale is desired. A notable feature of the Biophenometer is its durability. For example, during the second year of our study, the Biophenometer at site 2 withstood being submerged in several inches of rainwater, and few have failed to perform during the 10 years the SE PA IPM RG used the instrument. Other notable features are: the Biophenometer can be programmed to provide degree-days for a range of base temperatures and uses a standard averaging method to calculate degree-days (Table 2).

The Avatel HarvestGuard and Avatel Datascribe Junior instruments are considerably cheaper than the Wescor Biophenometer (Table 3). In addition to degree-days, the HarvestGuard can also provide the high and low temperatures for the current or previous day, which could be used to manually calculate degree-days to verify the instrument's readings. Like the Biophenometer, the HarvestGuard calculates cumulative degree-days, the data can be checked after any time interval, and the data are displayed on the instrument by pushing a button. Data from the Avatel Datascribe Junior were obtained by downloading the data to a personal computer with the complimentary software. At site 1, the device was brought inside to D.M. Caron's office to download. While it is being transported to the computer, a false temperature reading may occur during the programmed 15-min reading. The steps to compute degree-days for both Avatel products are listed in Table 2.

The Davis Weather Monitor II can measure many weather functions, such as temperature, humidity, barometric pressure, wind direction and speed, and wind chill. Software for the Weather Monitor II allows the user to enter degree-day thresholds for selected pest species. The instrument automatically downloads information, calculates degree-days, and outputs the

species name and when the threshold was reached for that species, or an estimate of when it will be reached. A downside is that the Weather Monitor II needs constant attachment to a power supply and computer. Many weather stations would not accommodate this need. Degree-day calculations using the Weather Monitor II occur via the integration or high-low method. However, the instrument uses a base temperature of 65 °F (18.3 °C) and could not be statistically compared to the other instruments and services, which use a base of 50 °F.

SkyBit is a weather data service that can be contracted to supply weather information from across the U.S., Mexico, and Canada. The data are sent electronically at daily intervals or at the client's specified time interval. The SkyBit service downloads data from approximately 25,000 National Weather Service temperature stations, but relies mainly on the approximately 11,000 aviation stations. Weather data is analyzed in 1-km grids (0.39 mile²), so barring a major change in topography, sites that are close in distance will have similar, if not exact, degree-day totals.

SkyBit uses hourly air temperature readings to calculate degree-days. When the air temperature is measured, SkyBit uses three-way quality control to correct for errors in the data. To calculate degree-days, the difference formula is used (Table 2).

Degree-days can be manually calculated from weather data using high and low daily temperatures. Manual calculations using weather data increase the risk of human error. Daily high and low temperatures can be supplied by a service or retrieved from sources such as the newspaper or websites; all data ultimately is supplied by a weather station. Many different formulas can be used to calculate degree-days (Higley et al., 1986; Pruess, 1983; Wang, 1960; Worner, 1992). To calculate degree-days when the high and low daily temperatures fell within the high and low thresholds, we used the averaging method (Table 2). This straightforward formula uses a 24-h block of time for calculation. When the daily low temperature fell below the lower threshold (50 °F), we used the single triangulation method (Table 2). This formula uses the required 24-h interval for calculation.

Using only high and low tem-

peratures may not accurately reflect the average weather during a particular day because the high and low temperatures may have only been sustained for a short time. The length of time that temperatures are sustained also affects insect development. Another factor that may affect degree-day totals derived from weather data are the amount of significant figures used during calculation. For example, using too many decimal points and decimal degree-days (i.e., <1) may misrepresent the season's total.

The other two instruments, the HOBO H8 Pro Temperature Data Logger and the Accu-Trax, were not included in the final statistical analysis. The HOBO Data Logger only measures temperature data and the data need to be downloaded to a computer in order to calculate degree-days manually. We did not find a practical way to standardize this among the three locations where it was used. The Accu-Trax stopped working multiple times within a 4-month trial period. When operational, the weekly degree-day accumulation fluctuated from unusually high to low compared to the other instruments and services.

Conclusion

All the instruments and the degree-day services analyzed statistically were comparable to each another. We found that none of the instruments or services varied significantly from each other because they all used the same general algorithm to calculate cumulative degree-days. Higley et al. (1986) provide a summary of several algorithms used to calculate degree-days and the similarities, limitations, and accuracy of each method. The primary difference between the instruments and services we evaluated was the frequency at which temperatures were sampled. Higley et al. (1986) indicate little variance between algorithms that use a 24- or 12-h period for calculation, but less is known about the effects of shorter sampling periods.

Secondary factors that may affect the variability of the degree-day accumulations are mechanical differences, including precision between the instruments and services. Since there was no statistical difference between the instruments and services, the selection of an instrument may be driven by other factors, like cost and personal preference. If a group, like the SE PA

IPM RG, is interested in measuring degree-days across a large region and distributing the information to group members, it would be best for the group to agree on a single instrument or service to use in order to accurately evaluate and compare information.

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