Effective Use of Models in the Management of Sooty Blotch and Flyspeck

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Introduction

During the 2010 growing season, in the process of developing sooty blotch/flyspeck recommendations for apple growers, Extension advisors in Massachusetts found they were getting very different disease forecasts for the disease depending on which model they used. In an attempt to determine what was behind these discrepancies, we compared five different methods for recommending the first SBFS fungicide spray at CSOREC in 2010. The five methods were the 270 ALW threshold from the New England Tree Fruit Guide with data from a Hobo Data Logger (Onset Computer Corp., Pocassett, MA); a Spectrum Watchdog weather station with the SpecWare SBFS model; Orchard Radar; Skybit; and NEWA with data from the on-site Hobo station. The results are shown in Figure 1.

This graph shows the large differences between the various models in terms of when the first fungicide application for SBFS was recommended. The earliest recommendation was June 2 (NEWA, Hobo) and the latest July 17 (SpecWare, Watchdog), a total difference of five weeks. The SpecWare recommendation was much later than any other. If it was excluded, the range between the other four models was two weeks, with the SkyBit model being the latest on June 16.

Unfortunately, we did not have trees that were sprayed according to each model, so we do not know whether these differences would have translated to control failures or over-application of fungicide. Under normal conditions, the differences in time would result in one to three applications of fungicide over the range of dates. What lies behind these differences? More importantly, what differences in performance would be expected between them?

Fundamentally, all SBFS forecast models measure periods when environmental moisture is high. They almost always use leaf wetness although relative humidity has been determined to be most effective in the Midwest. SBFS models add-up the number of hours of leaf wetness from a point called the biofix, usually at or near petal fall (PF). When a critical number of leaf wetting hours is reached, a fungicide spray is recommended. This point is the treatment threshold. Most SBFS models stop at this point, though some continue to evaluate SBFS risk based on estimates of fungicide residue on apples governed by the amount of time or the amount of rain since the last spray.
Underlying these models are four key ideas:

1. SBFS risk is very low until bloom;
2. Fungicides targeting apple scab will control SBFS through PF;
3. After primary scab it will take some time, depending on how much wet weather occurs, for SBFS inoculum to move into an orchard, colonize fruit, and develop the smudges and specks that are the signs of the disease;
4. Some fungicides can either eradicate SBFS fungi or stop their growth before signs develop.

Based on points 3 and 4, SBFS forecast models primarily try to take advantage of the period following the last apple scab fungicide to eliminate one or more cover fungicides, allowing SBFS to start to grow on apple fruit but stopping it before SBFS develops.

Because development of SBFS fungi cannot be observed directly, researchers have built SBFS models by keeping track of wetness data and observing when the first signs of SBFS appear. Data usually are taken over several years and at several sites, and then statistics are applied to determine which weather factor best

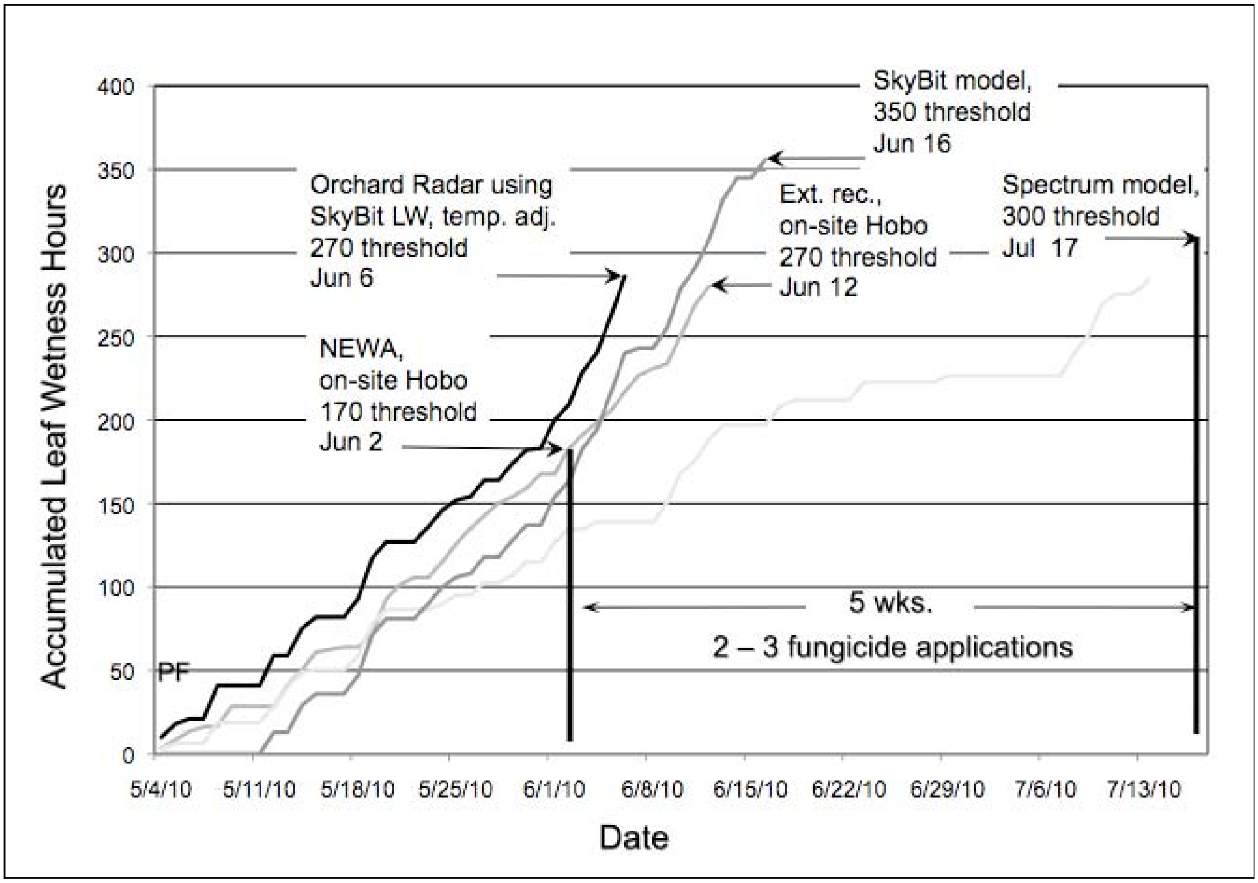

Figure 1. Graph of accumulated leaf wetness hours measured using different methods at the University of Massachusetts Cold Spring Orchard, Belchertown, MA vs. date, indicating the time recommended for the first fungicide application to manage sooty blotch and flyspeck for each method.

predicts first appearance of SBFS and when, on average, SBFS is first seen. Presumably, application of an appropriate fungicide before SBFS shows will prevent further disease development, so a treatment threshold is established shortly before first symptoms are predicted. In subsequent trials, fungicides are applied at the treatment threshold to make sure that the model works.

This type of model development does not depend on detailed knowledge of the microbiology of the disease, but on a statistical relationship between key environmental factors and the visible development of disease. Forecasting models developed this way are called empirical, and it's important that the type of data used to develop them is the same as the data used to run them in the field. Even then, trying to use an empirical model in a region that differs climatically or geographically from the place in which it was developed can result in poor disease management. In this article, we will look at the various SBFS models in use in terms of where and how they were developed, and attempt to clarify how they should be used in order to make SBFS management most effective. Key aspects of SBFS models are summarized and compared in Table 1.

Multiple Ways to Forecast SBFS

The first SBFS forecast model. Brown and Sutton developed the first SBFS model in North Carolina by taking weather data from 1987 to 1994 and comparing it to the first appearance of SBFS on fruit (4). The best predictor of when SBFS would show was leaf wetness duration (LWD) measured from 10 days after PF. They found that the best prediction came when they only counted those wetting periods that were 4 hours or longer. They added the number of leaf wetness hours for each day to give a single number, accumulated leaf wetness hours (ALWH). Over the 7 years of their tests, starting at a biofix of 10 days after PF, SBFS first appeared between 209 and 310 ALWH. The average threshold for first appearance was 273 ALWH. Based on this they recommended applying a benzimidazole fungicide, such as Benlate or Topsin M, at a treatment threshold of 200 to 225 ALWH to eradicate SBFS.

To get accurate results with this empirical model, it is important that ALWH be measured just as the model developers measured them. The NC researchers placed the device that measured leaf wetness inside the dripline of an apple tree, 1.5 meters (4½ ft.) above the ground. They used an instrument called a deWit monitor to measure leaf wetness. The deWit uses a string to move a pen on chart paper. A dry string is relatively taught holding the pen at one edge of the chart while a thoroughly soaked string is loose allowing the pen to move to the other edge of the chart. There is considerable distance between the edges of the chart, and it is not always clear whether the string is dry or wet, so deciding whether a leaf is wet or dry based on a deWit monitor is a judgment call. Brown and Sutton said movement across 50% of the chart or more indicated leaf wetness, but also said "… the threshold that we have established with the deWit sensor may have to be modified if other sensors are used" and noted

Table 1. List of major sooty blotch and flyspeck models describing the type of action being recommended, the biofix, the weather parameter used in calculating the threshold, the point at which first symptoms appear, and the treatment threshold.

Model	Biofix	ALWH accumulation	First symptoms	Treatment threshold	Recommended action
Brown/Sutton	10 days after PF[z]	LW[y] = 4 hrs.	273 hrs.	200 – 225 hrs.	1st benzimidazole fungicide
Brown/Sutton/ Hartman	10 days after PF[z]	All LW hrs.	218 hrs.[x]	175 hrs.	1st fungicide
Gleason/ Duttweiler	Date of last scab fungicide	RH[w] periods = 97% hrs. and = 4hrs.	192 hrs.	192 hrs.	1st fungicide
Rosenberger	PF	All LW hrs.[v]	540 hrs.	270 hrs.[v]	1st fungicide & follow-up[v]
Orchard Radar	PF	All LW hrs., temp. adj.	270 hrs.[u]	270 hrs.[u]	1st fungicide & follow-up
NEWA	PF	All LW hrs.	200 hrs.	175 hrs.[t]	1st fungicide & follow-up
Skybit	PF	All LW hrs.[s]	?	350 hrs.	1st fungicide
SpecWare	PF	LW = 3 hrs.	?	250 hrs. / 300 hrs.[r]	1st fungicide

[z]Petal fall.
[y]Leaf wetness.
[x]An average of the reported range, 185 to 251 hrs.
[w]Relative humidity
[v]As measured with a deWit monitor. Assumes application of at least one post-petal fall fungicide targeting scab.
[u]Temperature adjusted hrs.
[t]Measured electronically – interpolated from original deWit measurements.
[s]Leaf wetness is estimated from relative humidity, wind speed and other data.
[r]250 hrs. for "southern" orchards and 300 hrs. for "northern" orchards.

that a test of the model in Kentucky using an electronic sensor found a lower threshold. The type of wetness sensor and its location makes a great deal of difference in leaf wetness measurements, and using an electronic sensor to run a forecast model with thresholds based on a mechanical sensor like the deWit can be problematic. In other words, the researchers cautioned that if ALWH were measured with something other than a deWit monitor, the treatment threshold probably would change.

Revising the NC model. John Hartman in Kentucky tested the Brown/Sutton model, taking data with an electronic wetness sensor rather than a deWit. Realizing that the treatment threshold should be checked, he developed a method to protect fruit from SBFS fungi without using fungicides, using small paper bags. At regular time intervals of approximately one week, he bagged randomly selected fruit on trees in orchards. He found that fruit bagged during the weeks soon after petal fall did not develop SBFS, but fruit bagged later did. Specifically, SBFS first appeared from 185 to 251 ALWH depending on the site and year. Fruit bagged before 175 hrs. ALWH did not develop SBFS. Based on this, Hartman recommended a 175 ALWH treatment threshold. He also counted all wetting periods, not just those that exceeded 4 hours.

While the basic idea was the same as that developed in NC, Hartman used different equipment to measure wetting and a different method to determine when infections occurred and when symptoms would first appear from those infections - the paper bags. It is not surprising that this resulted in a large difference between the two treatment thresholds. Using the revised model, Hartman effectively controlled SBFS in the Kentucky trials, saving from two to four fungicide applications relative to calendar-based cover sprays (11, 20, 21).

This Hartman adaptation of the Brown/Sutton model was tested in three states in the upper Midwest in 2001-02 in both university trials and in commercial blocks (1, 9). In addition to testing the relative efficacy and application efficiency of the forecast model vs. conventional cover sprays, the study compared on-site weather measurement to off-site web-based measurements using SkyBit (ZedX, Inc., Bellefonte, PA). While the study generally reduced the number of fungicide applications by about 2, the model-managed plots often had significantly higher levels of SBFS. The study also indicated that the SkyBit measurements overestimated leaf wetness relative to electronic sensors placed in apple canopies.

As pointed out above, a forecast model developed in one region may perform poorly in another region, particularly if there are significant climatic differences. This may be what lies behind the inconsistent performance of the Hartman/Brown/Sutton model developed in the Southeast when it was applied to the upper Midwest. Duttweiler and colleagues (2, 7) suggested that during the growing season, the Midwest is significantly drier than the Southeast. While rain events provide the bulk of the leaf wetting periods measured in the Southeast, high humidity and dew provide most of the ALWH recorded in the Midwest. After examining other possible weather variables, the Iowa researchers found that accumulated periods of relative humidity greater than 97% provided better forecasts than LWD in the Midwest, though LWD performed better than humidity in the Southeast.

Adaptation of the NC model to the Northeast. In the Northeast, Rosenberger has developed an SBFS forecast model that is based on the fundamentals of the NC model and incorporates his extensive research on timing SBFS fungicide applications (19). His model is based on the idea that flyspeck is more difficult to control than sooty blotch and if flyspeck is controlled, sooty blotch is also controlled. The fungus that causes flyspeck in the Northeast, *Schizothyrium pomi*, produces primary inoculum starting around pink and continuing through to 3 or 4 weeks after petal fall when fruit are between 2 and 4 cm diam. (5). SBFS inoculum develops on reservoir hosts adjacent to orchards and is blown into apple trees. During the time that primary flyspeck inoculum is produced, apples are protected by fungicides applied to manage apple scab, so the primary infections pose no risk of SBFS to fruit. However the fungus can infect the waxy cuticles of the trees and shrubs adjacent to orchards, eventually growing to produce secondary inoculum, conidia. Based on the NC model, Rosenberger estimates that it takes approximately 270 ALWH from PF for inoculum in orchard borders to develop to the point that it is able to infect fruit. (The PF biofix and 270 ALWH are simplifications of the ALWH and biofix used in the NC model.)

After the intial 270 ALWH, Rosenberger estimates it takes an additional 270 ALWH for inoculum that lands on fruit to develop into ‘specks’. So, in his model, if fruit is unprotected by fungicide after scab applications have stopped, it will take a total of 540 ALWH for SBFS signs to develop. At any time after the first 270 ALWH, the process can be stopped by a fungicide application, but after the fungicide from an application is depleted (by tissue growth, oxidative and photochemical breakdown, and/or rainfall), SBFS fungi will start to develop again. Once fruit have been unprotected for a total of 540 ALWH, SBFS appears. This means a grower needs to know how long each fungicide is effective. Different fungicides have different effective periods, which Rosenberger has categorized in three groups based on time or rainfall from the last application: 1) 21 days or 2.5 in. rainfall; 2) 21 days or 2.0 in. rainfall; 3) 14 days or 1.5 in. rainfall.

Rosenberger’s model recommends the timings for both a first fungicide and for later fungicides. His specific recommendation is to apply the first fungicide at 270 ALWH from PF and to then allow no more than an additional 270 ALWH when fruit are unprotected by fungicide after that. Recently, Rosenberger has suggested that if electronic sensors are used, it may be more appropriate to use shorter thresholds of 175 ALWH before the first fungicide application followed by a 175 ALWH of unprotected fruit. The incorporation of efficacy periods into an SBFS model is unique among the SBFS models.

Based on these research studies, two Extension recommendations have been developed, and a third will probably be introduced next year. In the Midwest and Southeast, the Hartman/Brown/Sutton model is recommended, and in the Midwest this will probably change to the Gleason/Duttweiller adaptation based on relative humidity. In New York and New England, the Rosenberger model is generally recommended.

Adaptation of SBFS models in computerized delivery systems. Versions of the models described above have been adapted to computerized forecasting systems, merging automated weather data collection with model forecasts and recommendations. In the Northeast, Orchard Radar (http://pronewengland.org/allmodels/RadarIntro.htm) and the Network for Environment and Weather Applications (NEWA; http://newa.cornell.edu/) are web-based IPM advisory systems developed by the University of Maine and Cornell, respectively that incorporate SBFS advisory models. SkyBit is a web-based agricultural weather and advisory system developed by ZwdX, Inc. (Bellefonte, PA) that has an SBFS component. Commercial weather stations are often bundled with pest forecasting software. One example is the Watchdog (Spectrum Technologies, Plainfield, IL) which can be used with their SpecWare software, which includes a SBFS model.

Orchard Radar. Glen Koehler has developed Orchard Radar as a web-based pest management system for New England. For the most part it follows the Rosenberger model, except that LW data is adjusted for temperature based on *in vitro* growth data for the flyspeck fungus *Zygophiala jamaicensis* (17). Weather data is supplied by SkyBit and, for predictions, 30 year averages of historical weather data are used. Given application of a particular SBFS fungicide on a given date, Orchard Radar gives growers information on when the protection from that application ends (Protection End Date) and an estimate of when SBFS signs will first appear if no further applications are made. These estimates include a worse-case prediction for large, unpruned trees for a relatively wet year, and average prediction, and a prediction for low-risk sites (small, well-pruned trees, good air movement, significant distance from SBFS reservoir plants in orchard borders, etc.). Sample output for Orchard Radar is shown in Figure 2.

NEWA. The NEWA Sooty Blotch & Flyspeck Risk Prediction module also relies primarily on a simplified Rosenberger model, except that it uses threshold values of 170 ALWH rather than 270, to account for the fact that the data used by NEWA is largely from privately-owned weather stations on grower sites with electronic LW sensors. NEWA partners with the Northeast Regional Climate Center (Cornell Univ.) and through them uses data from airports and other public weather stations. However, LW is not available from these sites, so in the present version of the site SBFS risks are not given for those sites. For sites with LW monitoring, NEWA tracks LW from PF and asks growers to input the date of the most recent fungicide application. It then uses time and rainfall to estimate fungicide depletion (at present NEWA does not distinguish between fungicides in terms of depletion rates) and assigns three levels of risk (low, moderate, high) based on AWH from PF and fungicide depletion. The rules used in 2010 and sample output from the NEWA SBFS

Flyspeck prevention, Group A fungicides (strobilurins and Topsin M): August-September spray dates

Background Information for this page
Return to radar list for Belchertown MA

Weather data for Belchertown MA. Forecast values begin August 3, 2010

Continuous protection from June 6 until 30 days before harvest is recommended. Risk of new flyspeck infections increases around July 11, and increases again around August 10.

Flyspeck infections that begin before August 19 are likely to become visible around September 20. Infections that begin before September 2 are likely to become visible around October 20. But warm wet weather in September can accelerate flyspeck development resulting in earlier dates of flyspeck appearance before harvest.

Postinfection control of flyspeck may occur with application a strobilurin or Topsin M fungicide within 50 wet hours after the 'Protection end date' of the previous fungicide application.

Weather data for Belchertown MA. Forecast values begin August 3, 2010

Inches Rain	**Spray Date** - assumes that fungicide was applied before any rain fell on spray date	**Protection End Date** for full-dose **Pristine, Flint, Sovran,** or **Topsin M** (deadline for postinfection strobilurin or Topsin M)	**Date flyspeck infections that started after end of protection could appear** (Left side = rough estimate of flyspeck show date for dense canopy trees if weather beyond forecast range is in top 20% of years for both temperature and wet hours. x = show date is within forecast range. Right side = rough estimate of flyspeck show date for small, open canopy, low-risk trees.)		
0	**Sun, August 1**	**Aug 22** (August 27)	(Sep 13)	**September 25**	(> Oct. 31)
0	**Mon, August 2**	**Aug 23** (August 28)	(Sep 14)	**September 27**	
0	**Tue, August 3**	**Aug 24** (August 29)	(Sep 15)	**September 29**	
0	**Wed, August 4**	**Aug 24** (August 29)	(Sep 15)	**September 29**	
0	**Thu, August 5**	**Aug 24** (August 29)	(Sep 15)	**September 29**	
0.10	**Fri, August 6**	**Aug 24** (August 29)	(Sep 15)	**September 29**	

Figure 2. Computer screen output of information from the Orchard Radar Flyspeck module, taken on Aug. 2, 2010, showing the end of protection and subsequent first appearance of SBFS signs for six dates, based on SkyBit weather data for the Univ. of Mass. Cold Spring Orchard, Belchertown, MA. (More dates could be accessed on the actual screen.)

model shown in Figure 3.

SkyBit. SkyBit estimates weather variables for a specific site within a 1 km. square based on publically available weather data from many sites, and using proprietary algorithms. Growers supply SkyBit with the precise latitude, longitude and elevation of their site, and for a subscription fee receive estimates of what has happened, predictions of what will happen, and risk evaluations for various pests based on models. The SkyBit model uses the Brown/Sutton/Hartman model. However, based on extensive comparisons, SkyBit has determined that their estimated leaf wetness hours are generally higher than those that would be obtained from field measurements by a constant proportion, and therefore 350 AWH, rather than 270 AWH, is an appropriate threshold for the SBFS using SkyBit data. A sample of information received via email from SkyBit is shown in Figure 4.

Spectrum Watchdog and SpecWare. The WatchDog weather station is offered with a bundle of pest forecasting software, SpecWare. The documentation for the SBFS model in the SpecWare package infers that there are two models, one for sooty blotch and one for flyspeck, and says that “both models require air temperature and leaf wetness data” though none of the published models uses air temperature. The Spectrum model starts accumulating leaf wetness at PF, and has two infection thresholds, one for “Southern States” at 250 AWH and one for “Northern States” at 300 AWH. After that, any 3 hr. wetting period is enough for an infection. Apparently the Spectrum model is based on 1996 recommendations made by Jones and Sutton (13), though they start accumulation at 10 days after PF, and stress that the model is only meant to recommend timing for the first SBFS fungicide. Further, the 300 AWH is probably based on Jones’ interpretations of work done by Rosenberger at the time that suggested an effective interval of 300 hrs could be used with benzimidazole fungicides (18). The leaf wetness sensor for the Spectrum WatchDog has a range

	Accumulated Leaf Wetness Hours			
Days/Rain Since Petal Fall or Fungicide App	<100	100-129	130-170	>170
< 10 days, <= 1.5" rain	No Risk	Low	Low	Low
< 10 days, 1.51" - 2.0" rain	No Risk	low	Moderate	Moderate
< 10 days, >= 2.01" rain	No Risk	Low	Moderate	High
10-13 days, <= 1.5" rain	Low	Low	Low	Low
10-13 days, 1.51" - 2.0" rain	Low	Low	Moderate	Moderate
10-13 days, >= 2.01" rain	Low	Low	Moderate	High
14-20 days, <= 1.5" rain	Low	Low	Moderate	Moderate
14-20 days, 1.51" - 2.0" rain	Low	Low	Moderate	Moderate
14-20 days, >= 2.01" rain	Low	Low	Moderate	High
>=21 days, <= 1.5" rain	Low	Moderate	Moderate	High
>=21 days, 1.51" - 2.0" rain	Low	Moderate	Moderate	High
>=21 days, >= 2.01" rain	Low	Moderate	Moderate	High

Sooty Blotch and Flyspeck Risk Predictions for Deerfield

Petal fall date for McIntosh: 5/3/2010

Petal fall date above is estimated based on degree day accumulations or user input.
Enter the actual date for blocks of interest and the model will calculate the accumulated leaf wetness hours since petal fall more accurately.

Most recent fungicide application date: 7/20/2010

If petal fall has passed, enter the date of your most recent fungicide application.
If no fungicide applications have been made, do not enter a date.

In the Risk Summary table, note the accumulated leaf wetness hours since petal fall (Leaf Wetness Hours) and the Risk Level. Leaf wetness hours, rain events, and the last fungicide application date are taken into consideration in assessing risk level. To estimate risk in the near future, look at the probability of rain.

Consult the Risk Level IPM Guidelines below the **Risk Summary** table.

Sooty Blotch and Flyspeck Risk Summary - Northeastern US Model

	Past	Past	Current	5-Day Forecast	Forecast Details			
Date	Aug 1	Aug 2	Aug 3	Aug 4	Aug 5	Aug 6	Aug 7	Aug 8
Days since petal fall	90	91	92	-	-	-	-	-
Accumulated Leaf Wetness Hours - ALWH	784	786	790	-	-	-	-	-
Risk Level	Low	Low	Moderate	-	-	-	-	-
Rain Events and Fungicide Depletion Estimate								
Days since last fungicide application	12	13	14	-	-	-	-	-
Rain since last fungicide application	0.99	0.99	0.99	NA	NA	NA	NA	NA
Daily rain amount (inches)	0.00	0.00	0.00	-	-	-	-	-
Rain probability (%)			-|-	-|-	-|-	-|-	-|-	-|-

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Figure 3. Rules for evaluating sooty blotch and flyspeck risk in the NEWA system (2010) with sample output from Deerfield, MA for Aug. 3, 2010 based on a weather station at Clarkdale Orchards.

of 0 to 15, and the threshold for determining wet vs. dry can be set by the user; Spectrum recommends using 3 (20% of the range), though at the UMass CSOREC we have used 6 (40% of the range) which is similar to settings that we use with other electronic leaf wetness equipment. Output for the SBFS model and Spectrum weather station at the UMass CSOREC are shown in Figure 5.

E-WEATHER SERVICE — AGWEATHER IPM APPLE DISEASE PRODUCT

For: MA-BELCHERTOWN-HORTRESCENTER — Date: SUN Jun 20, 2010

	WEATHER					APPLE SCAB 100329				FIRE BLIGHT 100422				SOOTY BLOTCH 100502	
	TMX	TMN	PREC	ARH	LW	ASM	AW	TW	PW	ADH	AW	TW	PW	ALW	PW
Date	F	F	in	%	hr	%	hr	F		65F	hr	F		hr	
BASED ON OBSERVATIONS															
0601	76	61	0.51	85	17	100	12	71	++	225	12	71	++	154	+
0602	81	59	0.00	69	9	100	21	68	++	225	21	68	++	163	+
0603	78	63	0.23	81	20	100	11	73	++	225	11	73	++	183	+
0604	82	63	0.24	72	11	100	21	70	++	225	21	70	++	194	+
0605	82	67	0.42	77	22	100	11	76	++	225	11	76	++	216	+
0606	75	57	0.54	81	24	100	35	70	++	225	35	70	++	240	+
0607	70	52	0.00	55	3	100	38	69	++	225	38	69	++	243	+
0608	68	49	0.00	57	0	100	0	-	+	225	0	-	-	243	+
0609	64	45	0.39	76	12	100	12	58	++	225	3	62	++	255	+
0610	63	54	0.54	90	24	100	36	58	++	225	36	58	+	279	+
0611	69	55	0.00	79	12	100	48	58	++	225	48	58	+	291	+
0612	64	58	1.01	90	17	100	14	63	++	225	14	63	++	308	+
0613	65	60	0.12	91	24	100	38	63	++	225	38	63	++	332	+
0614	74	60	0.00	81	13	100	51	63	++	225	51	63	++	345	+
0615	76	54	0.00	62	0	100	0	-	+	225	0	-	-	345	+
0616	70	51	0.15	72	11	100	11	67	++	225	11	67	++	356	++
0617	69	57	0.06	81	10	100	21	65	++	225	21	65	++	366	++
0618	84	54	0.00	63	5	100	5	58	+	225	5	58	+	371	++
0619	82	57	0.00	66	0	100	0	-	+	225	0	-	-	371	++
BASED ON FORECASTS															
0620	82	65	0.00	75	5	100	5	68	+	225	5	68	++	376	++
0621	83	62	0.00	62	0	100	0	-	+	225	0	-	-	376	++
0622	74	60	----	69	0	100	0	-	+	225	0	-	-	376	++
0623	79	61	----	84	24	100	24	71	++	225	24	71	++	400	++

Figure 4. Sample information from SkyBit for the Univ. of Mass Cold Spring Orchard, Belchertown, MA from the June 20, 2010 email, showing both past and predicted weather on the far right (TMX = maximum temp. ºF; TMN = minimum temp. ºF; PREC = precipitation in inches; ARH = avg. relative humidity in percent; LW = leaf wetness hours for each day), and three disease models, one each for apple scab, fire blight and sooty blotch/flyspeck. The SBFS model is shown in the two columns on the far left (ALW = accumulated leaf wetness hours from PF; PW = pest warning), where + indicates the disease is active but infection has not occurred, and ++ indicates infection can occur on unprotected fruit. Note the change from + to ++ on June 16.

Written recommendations. Many fruit growers track weather data, but do not have a computerized models to process it and make recommendations for SBFS treatment. They can, however, use written recommendations such as *The New England Tree Fruit Management Guide*. It states "The real risk of flyspeck infection … occurs after approximately 270 hours of accumulated wetting (rains and dew periods) counting from petal fall" and "After spores land on unprotected fruit, 270 hr of accumulated wetting are required before flyspeck will become evident on fruit." In other words, it outlines the risk of infection according to the Rosenberger model. However, this guide does not include the fungicide depletion tables that Rosenberger developed.

The Special Problem of Measuring Leaf Wetness

In the descriptions above, it is obvious that

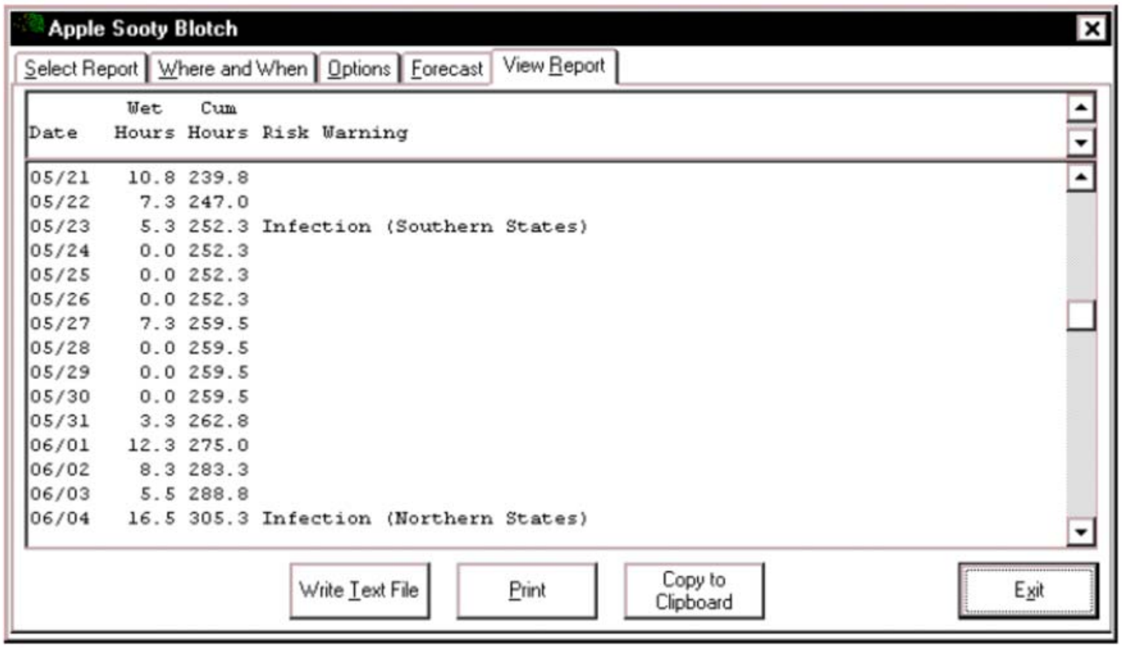

Figure 5. Output from the Spectrum Watchdog weather station at the Univ. of Mass. Cold Spring Orchard, Belchertown, MA in 2010, showing the predictions for potential infection for sooty blotch and flyspeck. Note infections can first occur in MA on June 4.

measurement of leaf wetness can be highly variable, depending on what sort of instrument is used, if any, and how sensors are placed. Again, data from Cold Spring Orchard illustrates the point. Figure 6 shows ALWH at the orchard based on five different sources: an Onset Hobo weather station with the leaf wetness threshold set to 40%; the same weather station with the leaf wetness threshold set at 100%; a Spectrum weather station with the threshold at 40%; Skybit; and an estimate based on airport weather data using a fuzzy logic algorithm (14). By June 12, the largest estimate of ALWH is over two and a half times greater than the smallest estimate.

While the differences are very large, the actual relationship between the different measurements is relatively constant. That means any of the estimates is acceptable **as long as it is used with an appropriate model and threshold.** For example, a user should not use SkyBit weather data to with a threshold developed using a string leaf wetness sensor.

The most common recommendation is to take measurements in the canopy of a typical tree in an orchard. Generally little attention has been paid to standardizing how high a LW sensor is placed above the ground, or which direction it should face, or if it should be placed at a specific angle. Recently, consensus has built around facing sensors north at a 45º angle relative to level (10). However, placing sensors in tree canopies can lead to practical problems because pesticides and other chemicals sprayed in an orchard can corrode the electronics in leaf wetness sensors. To avoid damaging sensors and ease access to the instruments, it would be useful to place sensors near but not in the orchard. To standardize the data, both researchers and growers should consider rules for placing sensors. For example, in addition to the rules for sensor angle and direction, these might include placement over mowed grass, at least 10 meters from any building or other physical features that could inhibit air circulation or effect microclimate.

Little emphasis has been placed on establishing what percent of an electronic sensor's response signifies "wet." If, for example, a company developed an SBFS model using sensors set to use 50% of the maximum to indicate a wet leaf surface, and a grower then uses the equipment and model with a setting of

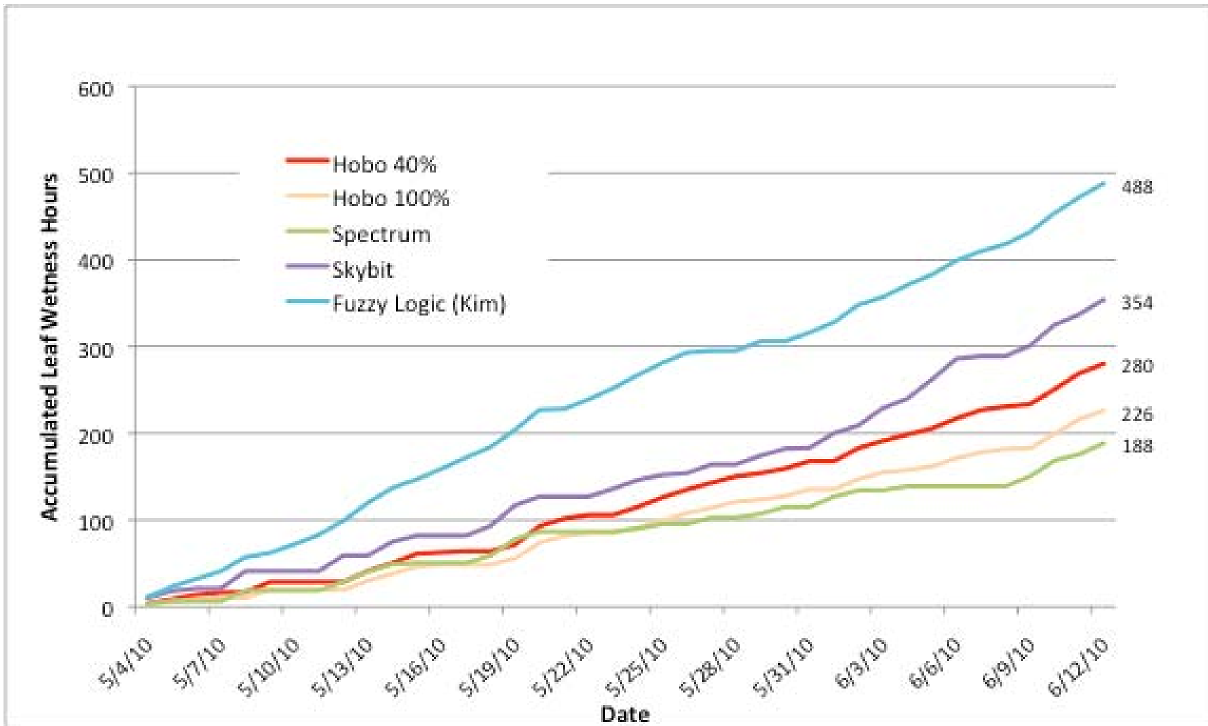

Figure 6. Accumulated leaf wetness hours at the Cold Spring Research and Education Center, Belchertown MA in 2010, measured using five different methods, with values on June 12 shown at the right of the graph.

10%, the grower will apply sprays sooner than necessary.

Even with such standardization in placing and calibrating equipment, there is a great deal of variability from sensor to sensor (16). Leaf wetness measurement is so variable that several researchers have recommended using off-site agricultural meteorological systems, such as SkyBit, rather than depending on on-site measurements (10, 16). One major issue is that publically available weather information of the type that is used in these systems do not supply LW data, so LW must be calculated based on the available data such as temperature, relative humidity and wind speed (14). Ultimately whatever LW measurement method is used needs to be evaluated within disease models. To take one measurement method and apply it to a model developed with a different method will lead to errors. For example, Babadoost et al. (1) applied the Brown/Sutton/Hartman model and compared on-site weather stations to SkyBit data (not the SkyBit model). Because SkyBit accumulates LW faster than on-site equipment, using SkyBit data with the 170 ALWH threshold meant fungicides were applied much sooner on SkyBit blocks compared with blocks timed by on-site equipment. While SkyBit has suggested that their 350 ALWH is equivalent to 270 ALWH measured by a deWit monitor or 175 ALWH measured by an electronic instrument, to our knowledge the 350 ALW threshold has not be tested in field trials to determine its performance within an appropriate model.

It would greatly help the accuracy of SBFS models (and all weather-based disease forecasting models) if LW measurement were better standardized, both at the time of model development and when it is used by growers. Researchers have pointed out that there no single “best” method to acquire weather data for use in disease-warning systems (10), but growers, consultants and researchers should make a concerted attempt to insure that data is being applied appropriately.

Summary and Conclusions

The biology and epidemiology of SBFS is not well understood and existing SBFS forecast models are largely empirical. The values of parameters in the models and recommendations they give users differ significantly. With this level of variability, it is useful to ask the fundamental question, what do users expect from a forecast model?

For SBFS the short answer is specific guidance in timing fungicide applications. Most SBFS models recommend a break in early cover sprays followed by the first SBFS spray. The length of the break is determined by some type of moisture measurement, usually accumulated leaf wetness hours. Most models then stop and growers use calendar-based covers. Other models continue, estimating fungicide depletion after each spray for different types of fungicides based on rainfall and elapsed time.

As shown above, growers in the Northeast can get widely divergent recommendations about timing the first SBFS fungicide application. There are three basic sources for this variability:

- The source of weather data, in particular leaf wetness.
- The biofix chosen to start a model.
- The method and amounts of accumulated wet hours used in determining a treatment threshold.

The variability of ALWH between different measurement techniques can be large, as shown above. This does not mean that any one method of measuring leaf wetness is better than another, but that researchers, consultants and growers must use the appropriate measurement method and threshold for a given model. Thresholds and measurement methods are not interchangeable.

The different biofixes in SBFS models, petal fall, 10 days after PF, and the last primary scab fungicide, are somewhat arbitrary, and not necessarily closely related to the epidemiology of the disease complex. Apple phenology is largely temperature driven, and if the development of SBFS fungi is also temperature driven, then apple phenology may provide a convenient and accurate biofix, but PF may not be the best growth stage to use. Work in MA on the flyspeck fungus *Schizothyrium pomi* showed that inoculum development is highly correlated with temperature starting with a green tip (‘McIntosh’) biofix. *S. pomi* ascospores start to develop near pink bud or bloom at 540 degree days (base 32ºF) and ends approximately 3 to 4 weeks after PF at 1,625 degree days (5). Hence, primary inoculum for flyspeck is available well before PF and continues to be available well after PF. In estimating the availability of FS inoculum, PF is not particularly relevant, while a biofix of green tip coupled with temperature data is.

To develop better SBFS models, it would be useful to know when inoculum is mature and able to infect fruit, the environmental conditions that lead to fruit infection, e.g. wetting, high humidity and/or temperature, and the amount of time related temperature, wetness and/or humidity that it takes for infections to develop into signs on fruit. This will probably mean developing separate models for inoculum development and for symptom development, just as there are separate models for these process for apple scab (8, 15, 22, 23). While some models, notably Rosenberger’s (19), suggest that ALWH at one point are related to inoculum development, and at another related to symptom development, the understanding of SBFS inoculum development and symptom development on fruit has not yet been closely studied. A clearer understanding of these aspects of SBFS epidemiology would undoubtedly improve forecast accuracy

Evidence to date suggests that inoculum is developing on reservoir hosts before fruit form, but that it does not move into orchards and infect until several days to several weeks after fruit set. In MA, while primary FS inoculum develops before bloom, conidia are not detected in orchards until 3 to 4 weeks after primary inoculum has been released (5). In NC, sooty blotch infections were initiated 10 to 21 days after PF (3). In KY fruit left unprotected by bags during the 175 ALWH starting 10 days after PF did not develop SBFS, but after that fruit without bags were infected. This research suggests that there is a period following fruit set when SBFS fungi grow on reservoir hosts but do not spread into orchards. By trapping spores of SBFS fungi at orchard borders, identifying them with appropriate PCR methods, it would be possible to relate inoculum development to temperature and/or moisture measurements.

Movement of SBFS inoculum into orchards does not necessarily mean that spores will successfully establish themselves on fruit. The specific conditions that enable SBFS fungi to colonize apple fruit remain largely unexplored. It is not clear that fruit need to be wet, or if they do, for how long. It may be that high humidity is sufficient to promote spore germination and growth. Again, temperature may also play a role.

No one really knows how long this period of invisible, or cryptic, growth is, because visible signs in the field may not appear until several weeks after SBFS fungi have landed on fruit and started to grow. Rosenberger has seen that newly infected apples harvested and stored at controlled levels of high humidity (essentially 100%) and at normal ambient temperatures (60º to 80º F) take at least 10 days to show SBFS (Rosenberger, unpublished). In the field, where humidity and temperatures fluctuate outside these optimal ranges for SBFS growth, it generally takes much longer for SBFS to show on fruit, though it is undoubtedly present. Some studies have shown the optimal conditions for growth under controlled laboratory conditions (12, 17), but these need to be related to actual infection and growth on apple fruit. In order to get a better estimate of the time it takes for symptoms to develop following infection, it would be useful to do bagging studies in orchards and controlled environment studies in the lab.

Unfortunately, the SBFS complex is very large, and species composition varies from region to region (6). Probably the development of different fungal species varies, meaning that developing a single set of inoculum development, infection and symptom development models for the entire complex may be problematic. However, in terms of practical management, it may be possible to time fungicide applications with a single set of models and achieve efficient SBFS control.

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