**Economic performance and comparative riskiness of different management practices for
control of Botrytis fruit rot in Florida strawberry**

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Abstract

Florida strawberry farmers usually rely on weekly calendarfungicide applications to prevent yield lossfromBotrytis fruit rot (BFR). The Strawberry Advisory System (SAS), which helps optimizethe timing of fungicide applications, is an additional tool in the farmers' arsenal of disease control options.This study uses data from two-year production trials in Floridacombined with historical strawberry prices to measure the economic performance of the Calendar and SAS-based BFR management practices under output price risk and producers' risk preferences.We use Monte Carlo simulation to model the effect of the variability in weekly output prices on farm returns. Results reveal that the traditional calendar-based system is not the least riskyBFRmanagement option as growers expected to be. SAS-based options such as SAS-Switch and SAS-Luna would be preferred by both risk-neutral and risk-averse producers and are recommended under high disease pressure conditions.

Keywords: strawberry production,Botrytis fruit rotmanagement, stochastic simulation, price risk, Florida

1.Introduction

Pest and diseases constitute major constraints in the production of agricultural crops and especially high-value crops such as fruit and vegetables. Pesticides are an important tool in controlling pest damage and optimizing the growingconditions for the target plants (Gurushankara, 2007; Cooper and Dobson, 2007). However, their indiscriminate use can lead to

adverse impacts on the environment (Skevas et al. 2013), such as the development of resistance in the pest population. An alternative to control pests and diseases and impose a lower burden on the environment is precision pesticide application. Under such a practice, decision makers account for site-specific conditions and field variability when making pest management decisions (Seelan, 2003). For instance, scouting and weather monitoring can be used to guide the optimal timing of pesticide applications. Precision pesticide applications can increase pesticide use efficiency, and decrease production costs and pesticide environmental spillovers (Jiaqiang et al. 2005).

A system that aims to optimize the timing of fungicide application in strawberry production is the Strawberry Advisory System (SAS) (Pavan et al, 2011). This system was first introduced in Florida, the second largest and the largest winter strawberry-producing state in the United States (NASS, 2015). Florida's humid and warm climate is favorable for fungal diseases such as Botrytis fruit rot (BFR) and anthracnose, which pose serious threats to strawberry production. SAS predicts conditions conducive for disease by using information on leaf wetness duration and average temperature during the wetness period (Vorotnikova et al, 2014). When conditions for disease development are optimal, SAS alerts producers of the need to apply fungicides. The web-based nature of the system allows strawberry farmers to subscribe to location-specific alerts (via text or e-mail messages) related to the timing and type of fungicide recommended.

Adopting precision agricultural technologies (PATs), such as SAS, depends on a variety of factors. In a review by Tey and Brindal (2012), the authors report seven broad categories of factors that influence the adoption of PATs: a) socio-economic, b) agro-ecological, c)

institutional, d) informational, e) behavioral, f) technological, and g) farmer perception. Farmers' perceived profitability by using PATs is a critical factor in adoption decisions (Walton et al. 2008; Tey and Brindal, 2012). Producers will adopt a new pest management technique if the economic returns from applying this technique are at least equal to returns from the most profitable conventional alternative. Adoption decisions may also be affected by the perceived risk of adopting an innovation (Marra et al, 2003; Chavas, et al., 2010). Farmers' risk attitudes (Just and Zilberman, 1983) and perception about the distribution of future payoffs from the new technology (Marra et al, 2003) do affect the uptake of emerging agricultural technologies.

To date, there is very little attention given to the economic viability and riskiness of PATs in strawberry production (Vorotnikova et al. 2014). Strawberries are highly perishable fruits and their market price is volatile. Output prices could change dramatically week from week because of the perishability coupled with varying supplies due to the yield waves over the season. However, there is no analysis in the literature accounting for this important issue. Given that strawberry prices present a considerable weekly variation (Trumble and Morse, 1993, Haydu and Legard, 2003) due to elements that are not under the control of the decision maker (e.g. seasonality, climatic and pest events, imports from other strawberry producing regions), assuming annual variation in output prices when modeling the economic performance of strawberry production systems can yield incorrect results. This study adds to the literature that models the economic performance of different strawberry pest management practices under a stochastic decision environment in two important ways. First, it considers explicitly the impact of weekly output price risk on the economic performance of different BFR management strategies in Florida strawberry production. Second, it compares the profitability of the most

commonly used pest management strategy (i.e. calendar weekly treatment) with eight different fungicides used under SAS (including some plant protection products which are yet to be authorized for commercial use). The use of a more detailed representation of output price risk when modeling strawberry farmers' production environment, and the examination of the comparative riskiness of a broad range of SAS practices provides a more accurate and richer picture of the ranking of available BFR management options in strawberry production. This, in turn, will assist growers in choosing the BFR management technique that will provide them with the most benefits.

2. Materials and methods

2.1 Conceptual framework

This section establishes the conceptual framework of a model that accounts for the role of risk in BFR management decision making. Rational decision makers are assumed to make BFR management choices by maximizing their profits (π) from strawberry production:

$$\text{Max}_j \pi_j \quad (1)$$

where π_j denotes profit under disease management strategy j .

The approach to use when ranking different BFR management strategies in terms of economic viability will depend on the individual's level of aversion to risk. When assuming a risk-free environment (i.e. risk-neutral farmer), ranking alternative disease management strategies can be done by using (1). Conversely, under an environment of risk and uncertainty and when the decision maker is risk-averse, preferences over the probability distribution of uncertain outcomes

matter. Hence, differences in probability distributions of stochastic outcomes for different levels of risk need to be examined. Revenue uncertainty due to fluctuations in crop output prices is a key challenge in annual crops' production. Agricultural prices vary due to changes in markets, which vary spatially from local to global (Harwood et al, 1999). Next, we present the empirical methods used to analyze how output price risk is likely to affect farmers' decisions about adopting different BFR management practices.

2.2 Empirical model

In order to examine the effect of risk on farmers' decisions about adopting different BFR management practices, we compare results from partial budgeting to those from stochastic simulation. Partial budgeting is a technique for assessing the profitability of alternative production systems by considering only those items of benefits and costs that change (Wossink and Osmond, 2002). Stochastic simulation allows developing probability distributions of profits that allow comparison of the economic performance of different BFR management options over a broad range of output price conditions and for decision makers with different levels of risk aversion. We first describe methods for partial budgeting analysis, then we move to methods for stochastic simulation and comparison of probability distributions of profits.

2.2.1 Risk-neutral case: partial budgeting analysis of BFR management alternatives in strawberry production

Partial budgeting is used to compute the economic performance of strawberry production systems using different BFR management strategies. Revenues and expenditures are used to

calculate profits for each production system. Farmer's profit under BFR management strategy j is calculated using the following formula:

$$\pi_j = \sum_{w=1}^W (P_w Y_{wj}) - C_j \quad (2)$$

where w , P , Y , and C denote week, output price, strawberry yield, and production costs, respectively. Concerning expenditures, the only costs that vary across treatments are the fungicide and spraying costs. All other costs (e.g. fertilizer, labor, land rent) are fixed, and therefore excluded from the partial budgeting model.

The rationale behind using weekly revenues (*i.e.* $P_w Y_{wj}$) is that farmers' revenues vary as a result of weekly variation in strawberry prices (Trumble and Morse, 1993, Haydu and Legard, 2003; Mohapatra et al., 2010).

2.2.2 Risk-averse case: Stochastic simulation

The stochastic simulation model builds on the partial budgeting approach to compute economic returns from using different BFR management strategies. The steps involved in building the stochastic (Monte Carlo) simulation model are detailed below. They include: a) collection of suitable random price data, b) synthesis of random price data and deterministic yields and production costs into a stochastic simulation of profit distributions by BFR management strategy, and 3) analysis of results using stochastic dominance (SD) criteria.

Weekly strawberry prices were drawn at random from distributions derived from weekly mean prices in a 16 year (*i.e.* 2000-2015) historical database from the United States Department of

Agriculture (USDA). To account for the fact that strawberry prices are affected by strawberry supply, weekly strawberry yields were retrieved from USDA for 2000 to 2015 and correlation coefficients between weekly yields and prices were calculated and incorporated in the stochastic simulation.² The stochastic simulation model was built in Excel with the add-in program @Risk.

Figure 1 presents the steps performed in implementing the stochastic simulation. As shown in Figure 1, the analysis starts by loading the weekly strawberry yields and seasonal fungicide and spraying costs. Each BFR management simulation cycle begins by drawing twelve strawberry prices, each for one of the twelve weeks of the production season, then with weekly strawberry yields and production cost, it calculates annual profit. The simulation cycle is repeated 1000 times. Upon completion of the 1000 simulation runs, cumulative distributions are constructed by ordering outcomes from smallest to largest.

The risky alternatives are then compared using stochastic dominance (SD) criteria. These criteria allow comparison between empirical distributions of risky alternatives without requiring explicit knowledge of individuals' preferences or welfare function. First (FSD) and second degree stochastic dominance (SSD) are common SD criteria that provide a partial ordering of risky alternatives given risk aversion. FSD assumes that decision makers prefer higher to lower returns and the preferred alternative is the one that provides a higher outcome at every level of probability. FSD covers all risk preferences. SSD further assumes that the decision maker is risk averse. Both approaches involve pairwise comparisons of the Cumulative Distribution Functions

² Historical yield and price data confirm the presence of correlation between state-level weekly yields and prices. The average correlation was -.56, ranging from -.26 in week 9 (i.e. early February) to -.73 in week 5 (i.e. early January).

(CDF) of profits from alternative production options. When FSD and SSD cannot provide a complete ranking of alternatives, an approach with more restrictive assumptions but stronger discriminating power is stochastic efficiency with respect to a function (SERF)(Hardaker et al., 2004)³.

Figure 1. Flow chart of stochastic simulation of annual profit.

3. Data

We use capital budgets based on field trials of twelve different BFR management strategies used on the strawberry research sites of the Gulf Coast Research and Education Center (GCREC)

³ As shown in our results (section 4.2), SERF was not used since only one disease management option in both seasons dominated all other systems under FSD or SSD. Therefore, a detailed description of the SERF approach is not provided at this point. Interested readers can find such a description in Hardaker et al. (2004).

176 in Wimauma, Florida, between 2013 and 2015. The trials were conducted to assess the
177 effectiveness of different BFR management strategies in controlling BFR which is one of the most
178 important diseases in strawberry production and is mainly controlled by preventive fungicide
179 applications (Washington et al., 1992, Wedge et al., 2007). The strawberry cultivar used in the
180 experiments was Winterstar, which is medium susceptible to BFR. A randomized complete block
181 design with four, and three replications was followed in 2013-2014, and 2014-2015 season,
182 respectively. One plastic-mulched raised bed was used, per replication. Each replication had nine
183 and ten treatments in 2013-2014, and 2014-2015 season, respectively. Table 1 presents the
184 fungicide treatments, application rates, and frequency of applications for each treatment in each
185 production season. In 2013-2014 the fungicide treatments were the following: Calendari.e.
186 fungicide applications weekly (standard treatment including Captan 80 WDG, Thiram, Captevate
187 and Switch), non-treated control, SAS Thiram 24/7 (Chemtura Corporation, Middlebury, CT),
188 SAS Captevate (Arysta Life Science, Cary, NC), SAS Switch (Syngenta Crop Protection,
189 Greensboro, NC), SAS Pristine (BASF Corporation, Research Triangle Park, NC), SAS Scala
190 (Bayer Crop Science, Research Triangle Park, NC), SAS Fontelis (DuPont, Wilmington, DE) and
191 SAS Luna Privilege (Bayer Crop Science). The 2014-2015 treatments were the same except for
192 SAS Merivon (BASF Corporation) which replaced SAS Pristine, and SAS Luna Tranquility
193 (Bayer Crop Science) which replaced SAS Luna Privilege, and the addition of SAS Thiram 24/7
194 + Fontelis. The non-treated controls served to indicate the favorability of the weather conditions
195 for disease development each year in the absence of fungicide applications. Different fungicide
196 products were used in the two years because of some changes in product availability, i.e. Luna
197 Privilege vs Luna Tranquility (from Bayer Crop Science) and Pristine vs Merivon (from BASF
198 Corporation). The SAS-based treatments included fungicide applications following SAS

recommendations. The standard treatment was the Calendar system consisting of weekly fungicide applications as it is the most commonly used BFR management strategy by strawberry growers in Florida.

The Calendar weekly treatment had the highest number of fungicide applications. The number of fungicide applications for the SAS-based systems were eight and nine in 2013-14 and 2014-15, respectively. The main fungicide in each SAS-based system (e.g. Switch in SAS Switch) was applied four times during each production season when weather conditions were highly conducive for BFR development (according to SAS alerts) and bloom was present. The remaining applications were protectant fungicides (i.e. Captan 80 WDG, Thiram) applied when weather conditions were only moderately favorable and plants were not blooming.

Table 1. BFR management strategies in 2013-14 and 2014-15 seasons, application rates, and frequency of fungicide applications.

Treatment type	Fungicide	Rate in kg/ha	# applications
2013-2014 season			
Untreated	NA	NA	-
Calendar - Std Weekly	Captan 80 WDG	2.09	8
	Switch	1.02	1
	Captevate	4.87	3
	Captan 80 WDG	3.34	3
SAS Thiram	Captan 80 WDG	2.09	2
	Thiram	3.56	6
SAS Captevate	Captan 80 WDG	2.09	2
	Captevate	4.87	4
	Thiram	3.56	2
SAS Switch	Captan 80 WDG	2.09	2
	Switch	1.02	4
	Thiram	3.56	2
SAS Pristine	Captan 80 WDG	2.09	2
	Pristine	1.68	4
	Thiram	3.56	2
SAS Scala	Captan 80 WDG	2.09	2
	Scala	1.31	4

	Thiram	3.56	2
SAS Fontelis	Captan 80 WDG	2.09	2
	Fontelis	1.75	4
	Thiram	3.56	2
SAS Luna Privilege	Captan 80 WDG	2.09	2
	LunaPrivilege	0.50	4
	Thiram	3.56	2
2014-2015 season			
Untreated	NA	NA	-
Calendar - Std Weekly	Captan 80 WDG	2.09	4
	Switch	1.02	3
	Captevate	4.87	2
	Captan 80 WDG	3.34	4
	Thiram 24/7	3.48	1
SAS Thiram 24/7	Captan 80 WDG	2.09	4
	Thiram 24/7	3.48	5
SAS Captevate	Captan 80 WDG	2.09	4
	Thiram 24/7	3.48	1
	Captevate	4.87	4
SAS Switch	Captan 80 WDG	2.09	4
	Thiram 24/7	3.48	1
	Switch	15.57	4
SAS Merivon	Captan 80 WDG	2.09	4
	Thiram 24/7	3.48	1
	Merivon	0.40	4
SAS Scala	Captan 80 WDG	2.09	4
	Thiram 24/7	3.48	1
	Scala	1.31	4
SAS Fontelis	Captan 80 WDG	2.09	4
	Thiram 24/7	3.48	1
	Fontelis	1.75	4
SAS Luna Tranquility	Captan 80 WDG	2.09	4
	Thiram 24/7	3.48	1
	Luna Tranquility	1.46	4
SAS Thiram 24/7 + Fontelis	Captan 80 WDG	2.09	4
	Thiram 24/7	3.48	5
	Fontelis	1.75	4

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Data on weekly strawberry prices for the period 2000-2015 were retrieved from USDA (USDA, 2015). For the deterministic partial budgeting analysis, average weekly strawberry prices for the period 2013-2015 were used. On the other hand, the stochastic capital budgeting analysis utilizes prices that were drawn randomly from distributions of weekly prices from the period 2000-2015. Weekly prices cover 12 weeks, from early December (i.e. December 15) till early April (i.e. April 4). These prices vary from an average of \$22/flat in early December to \$10/flat in early April. Strawberry prices are higher in the beginning of the harvest season (i.e. end of December). Early winter production provides a limited window for high profits due to lower competition with other strawberry producing regions (e.g. California, Mexico) (Torres-Quezada et al., 2015).

4. Results and discussion

4.1 Cropping systems' yield, profitability, and related BFR pressure

Table 2 shows strawberry yields and fungicide costs by BFR management strategy. The harvest period lasted 8 and 12 weeks in the 2013-2014 and 2014-2015 seasons, respectively. SAS Switch and SAS Luna Privilege had the highest yields in the 2013-2014 season, while SAS Switch achieved the highest yield in the 2014-2015 season. The lowest yields are found in the non-treated controls in both production seasons, and the SAS Scala treatment in 2013-2014. The low yields of the non-treated control treatments might be explained by BFR losses in the absence of disease control. The relatively poor performance of SAS Scala in terms of yield, shows its low effectiveness in controlling BFR. Yields from each BFR management strategy were compared by means of the Kolmogorov-Smirnov (K-S) test. The K-S test statistic is a distribution-free nonparametric test that looks for differences in both shape and location of empirical distributions

(in our case the weekly yield distributions). According to the K-S results (Table A1, A2), significant yield differences are observed (in both seasons) between the Untreated and SAS-based systems, and between SAS Scala and Calendar-Stdweekly and other SAS-based treatments.

The cost of the fungicide treatments comprises the cost for fungicides, and the cost of labor for spraying. The Calendar weekly treatment in both seasons had the highest fungicide and spraying costs since it involves the highest number of fungicide applications (Table 2).

Table 2. Seasonal yield and fungicide costs under different BFR management strategies.

Treatment	Yield (Mg/ha)	Fungicide cost (\$/ha)	Spraying cost (\$/ha)
2013-2014 season			
Untreated	68	0	0
Calendar - Std Weekly	79	664	519
SAS Thiram	81	353	277
SAS Captevate	76	546	277
SAS Switch	90	690	277
SAS Pristine	71	796	277
SAS Scala	65	397	277
SAS Fontelis	82	492	277
SAS Luna Privilege	90	526	277
2014-2015 season			
Untreated	84	0	0
Calendar - Std Weekly	113	834	519
SAS Thiram 24/7	114	262	334
SAS Captevate	90	513	334
SAS Switch	118	658	334
SAS Merivon	102	442	334
SAS Scala	97	364	334
SAS Fontelis	105	459	334
SAS Luna Tranquility	108	498	334
SAS Thiram 24/7 + Fontelis	107	613	482

The profitability of the BFR management strategies is presented in Figures 2 and 3. A few SAS-based treatments in both seasons outperformed the Calendar system. More specifically, in 2013-2014 the most profitable BFR management strategy was SAS Luna Privilege, followed by SAS Switch, SAS Fontelis, and the Calendar system. In 2014-2015, the Calendar system ranked third after SAS Thiram 24/7, and SAS Switch.

Figure 2. Profit (\$1,000 ha⁻¹) by BFR management strategy in 2013-2014.

Figure 3. Profit (\$1,000 ha⁻¹) by BFR management strategy in 2014-2015.

Table 3 presents the average percentage of BFR infected fruit by treatment in 2013-2014 and 2014-2015 seasons. BFR incidence was high in 2014-2015 compared to the earlier season (i.e. 2013-2014). Average BFR level for the non-treated control in 2014-2015 was 26.4% compared to 19.4% in 2013-2014. SAS Switch appears as the treatment that most effectively controlled BFR in both seasons, followed by SAS Luna Privilege, and Calendar in 2013-2014, and by SAS Luna Tranquility in 2014-2015. The K-S results (Table A1, and A2) show no significant differences in BFR levels among these treatments, but significant differences are reported between these treatments and most other treatments. The fact that Calendar is not the most effective system in controlling BFR in conjunction with its high fungicide-related cost (Table 2) implies that strawberry farmers can reduce BFR incidence and improve their profitability by using alternative SAS-based BFR management practices such as SAS Switch.

Table 3. Average percentage level of Botrytis fruit rot (BFR) percentage by BFR management strategy in 2013-2014 and 2014-2015 seasons.

2013-2014		2014-2015	
Treatment	Average percentage (%) level of BFR	Treatment	Average percentage (%) level of BFR
Untreated	19.4	Untreated	26.4
Calendar - Std Weekly	11.5	Calendar - Std Weekly	14.8
SAS Thiram	13.0	SAS Thiram 24/7	15.8
SAS Captevate	15.2	SAS Captevate	14.0
SAS Switch	7.2	SAS Switch	8.7
SAS Pristine	19.2	SAS Merivon	16.1
SAS Scala	24.3	SAS Scala	20.6
SAS Fontelis	13.1	SAS Fontelis	14.3
SAS Luna Privilege	8.0	SAS Luna Tranquility	10.2
		SAS Thiram 24/7 + Fontelis	13.7

The following stochastic analysis examines BFR management systems' performance under weekly output price risk and farmers' risk attitudes about the distribution of payoffs from the different systems.

4.2 Stochastic simulation results

Up to this point, all results have been based on mean values, so they ignored output price risk and farmers' risk preferences. Simulated profits to Calendar and SAS-based systems were computed using stochastic simulation as described in section 2. These systems were then ranked using SD criteria.

Cumulative distribution functions (CDFs) based on profits for different BFR management practices for 2013-14 are presented in Figure 4. SAS Scala lies to the left of all the other BFR management practices and hence is FSD dominated by almost all these practices.⁴ SAS Luna Privilege and SAS Switch are the least risky BFR management options as their CDFs lie farthest to the right of the CDFs of all other options. A pairwise comparison of these two alternatives using FSD would eliminate none of the two from the efficient set. Hence, a higher order stochastic dominance analysis is needed to rank these alternatives. SAS Switch was dominated by SAS Luna Privilege under SSD.

⁴ An exception was the untreated system that dominated SAS Scala under SSD in 2013-2014.

Figure 4. Cumulative probability distribution functions based on profits for different Botrytis fruit rot management practices over the period 2013-14.

Figure 5, shows the same results as in Figure 4 but for the 2014-15 season. SAS Scala is again the most risky SAS-based BFR management option as it lies to the left of all other BFR management options functions (except for the untreated one). SAS Switch is the least risky BFR management practice as it lies to the right of all the other options' functions. SAS Switch dominates SAS Thiram but below 15% the functions are crossing each other and needs a higher order stochastic dominance analysis to decide which one is best. By SSD, SAS Switch dominates SAS Thiram. The non-treated control was dominated by almost all other treatments under FSD in both seasons.⁵ Since only one BFR management system remained in the risk efficient set in both production seasons (i.e. in the sense that were not dominated by any other system under FSD and

⁵ The only system that was dominated (under SSD) by the non-treated system was SAS Scala in 2013-2014.

SSD), it is not necessary to rank the set of BFR management systems using alternative approaches that have stronger discriminating power than FSD and SSD (e.g. SERF).

On comparing the partial budgeting (i.e. risk-neutral case) and the stochastic simulation (i.e. risk-averse case) results, we see both similarities and differences in the ranking of risky BFR management systems. The industry standard system (i.e. Calendar) is not the dominant BFR management practice under the risk-neutral and the risk-averse case and in both production periods. The most prominent difference when comparing the results of the risk-neutral and the risk-averse case is the change in the ranking of the best performing SAS-based system in 2014-2015 (i.e., SAS Switch ranks second in the risk-neutral case, while in the risk-averse case it takes the first place). Ordering changes when moving from the risk-neutral to the risk-averse case are attributed to the fact that stochastic simulation covers a wide range of states of nature.

Figure 6. Cumulative probability distribution functions based on profits for different Botrytis fruit rot management practices over the period 2014-15.

Some caution is needed when interpreting the ranking results of this study. When a specific SAS-based system ranks higher than all other treatments, it does not necessarily mean that strawberry growers should only rely on this specific BFR management strategy to prevent output loss. In reality SAS provides different recommendations for types of fungicides to be applied in strawberry production depending on location-specific BFR pressure conditions. The fact that this analysis shows that SAS Luna Privilege performed better than all other treatments under the 2013-2014 conditions and SAS Switch outperformed all other practices in 2014-2015, implies that those two fungicides should be used under highly BFR-conducive conditions. However, in order to avoid fungicide resistance development, it is recommended to use these fungicides interchangeably.

5. Conclusions

This study supplements standard partial budgeting with stochastic simulation to assess the effectiveness of BFR management practices in Florida strawberry production. We use capital budgets from 2013-2015 from GCREC at Wimauma, FL, and historical weekly strawberry prices to simulate output price risk that affects returns from strawberry production.

The results of the standard partial budgeting analysis show that Calendar, which is the most commonly used BFR management strategy in Florida strawberry production, was outperformed by a notable number of SAS-based options (i.e., SAS Switch, SAS Luna Privilege, SAS Thiram, and SAS Fontelis). The higher effectiveness in controlling BFR incidence compared to that of

Calendar, and the fact that Calendar has higher fungicide-related costs make some of the SAS-based systems more profitable than Calendar.

This result is also confirmed by the stochastic analysis that accounts for weekly output price risk and farmers' risk attitudes. Under this analysis SAS Luna Privilege and SAS Switch dominated all other BFR management options in 2013-2014 and 2014-2015, respectively. Both risk-neutral and risk-averse farmers would prefer these practices compared to Calendar and other SAS-based treatments. An earlier study that assessed the profitability and comparative riskiness of Calendar and SAS-based practices also found that the latter are the preferred methods of fungicide application (Vorotnikova et al. 2014). However, our study offers more precise recommendations on specific SAS-based systems to be used under different BFR pressure conditions. Even though only one fungicide was used in each treatment of our study, it is recommended that SAS Luna Privilege and SAS Switch be used in alternation under high BFR pressure conditions to avoid resistance development in the target pathogens. As noted earlier, the overall BFR management strategy also includes the use of protectant fungicides (i.e. Captan 80 WDG, Thiram) when weather conditions are moderately favorable. Future studies should assess the economic benefits of SAS recommendations where more than 2 fungicides are used to avoid resistance development.

Overall, the results show evidence of potential economic gains from switching from Calendar to certain SAS-based options. Precision pesticide applications, such as the SAS-based options examined in this study, have shown to decrease pesticides' environmental and health spillovers. For instance, precise use of pesticides can protect beneficials, such as natural enemies of insect

pests and pollinators, allowing farmers to reap the potential benefits of agricultural biocontrol and pollination. Future research could examine whether the comparative advantage of the most promising SAS-based options found in this study, can be further underlined by accounting for the effect of switching to such options on the environment and farmworkers' health.

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449 Appendix

450 Table A1. Kolmogorov–Smirnov tests of yields and Botrytis fruit rot (BFR) pressure from different treatments in 2013-14(*P*-values
451 for two-sided tests).

Null hypothesis	p-value	Null hypothesis	p-value
Yields from Untreated and Calendar-Std Weekly are same	0.021	BFR pressures from Untreated and Calendar-Std Weekly are same	0.036
Yields from Untreated and SAS Thiram are same	0.212	BFR pressures from Untreated and SAS Thiram are same	0.303
Yields from Untreated and SAS Captevate are same	0.555	BFR pressures from Untreated and SAS Captevate are same	0.704
Yields from Untreated and SAS Switch are same	0.093	BFR pressures from Untreated and SAS Switch are same	0.002
Yields from Untreated and SAS Pristine are same	0.704	BFR pressures from Untreated and SAS Pristine are same	0.555
Yields from Untreated and SAS Scala are same	0.944	BFR pressures from Untreated and SAS Scala are same	0.303
Yields from Untreated and SAS Fontelis are same	0.093	BFR pressures from Untreated and SAS Fontelis are same	0.303
Yields from Untreated and SAS Luna Privilege are same	0.059	BFR pressures from Untreated and SAS Luna Privilege are same	0.012
Yields from Calendar-Std Weekly and SAS Thiram 24/7 are same	0.704	BFR pressures from Calendar-Std Weekly and SAS Thiram 24/7 are same	0.303
Yields from Calendar-Std Weekly and SAS Captevate are same	0.303	BFR pressures from Calendar-Std Weekly and SAS Captevate are same	0.021
Yields from Calendar-Std Weekly and SAS Switch are same	0.704	BFR pressures from Calendar-Std Weekly and SAS Switch are same	0.143
Yields from Calendar-Std Weekly and SAS Pristine are same	0.303	BFR pressures from Calendar-Std Weekly and SAS Pristine are same	0.093
Yields from Calendar-Std Weekly and SAS Scala are same	0.093	BFR pressures from Calendar-Std Weekly and SAS Scala are same	0.004
Yields from Calendar-Std Weekly and SAS Fontelis are	0.843	BFR pressures from Calendar-Std Weekly and SAS	0.704

same		Fontelis are same	
Yields from Calendar-Std Weekly and SAS Luna Privilege are same	0.555	BFR pressures from Calendar-Std Weekly and SAS Luna Privilege are same	0.059
Yields from SAS Thiram 24/7 and SAS Captevate are same	0.843	BFR pressures from SAS Thiram 24/7 and SAS Captevate are same	0.555
Yields from SAS Thiram 24/7 and SAS Switch are same	0.418	BFR pressures from SAS Thiram 24/7 and SAS Switch are same	0.059
Yields from SAS Thiram 24/7 and SAS Pristine are same	0.944	BFR pressures from SAS Thiram 24/7 and SAS Pristine are same	0.555
Yields from SAS Thiram 24/7 and SAS Scala are same	0.418	BFR pressures from SAS Thiram 24/7 and SAS Scala are same	0.012
Yields from SAS Thiram 24/7 and SAS Fontelis are same	0.555	BFR pressures from SAS Thiram 24/7 and SAS Fontelis are same	0.843
Yields from SAS Thiram 24/7 and SAS Luna Privilege are same	0.143	BFR pressures from SAS Thiram 24/7 and SAS Luna Privilege are same	0.093
Yields from SAS Captevate and SAS Switch are same	0.555	BFR pressures from SAS Captevate and SAS Switch are same	0.004
Yields from SAS Captevate and SAS Pristine are same	0.944	BFR pressures from SAS Captevate and SAS Pristine are same	0.843
Yields from SAS Captevate and SAS Scala are same	0.555	BFR pressures from SAS Captevate and SAS Scala are same	0.036
Yields from SAS Captevate and SAS Fontelis are same	0.555	BFR pressures from SAS Captevate and SAS Fontelis are same	0.303
Yields from SAS Captevate and SAS Luna Privilege are same	0.418	BFR pressures from SAS Captevate and SAS Luna Privilege are same	0.036
Yields from SAS Switch and SAS Pristine are same	0.303	BFR pressures from SAS Switch and SAS Pristine are same	0.012
Yields from SAS Switch and SAS Scala are same	0.059	BFR pressures from SAS Switch and SAS Scala are same	0.000
Yields from SAS Switch and SAS Fontelis are same	0.555	BFR pressures from SAS Switch and SAS Fontelis are same	0.212
Yields from SAS Switch and SAS Luna Privilege are same	0.944	BFR pressures from SAS Switch and SAS Luna Privilege are same	0.944

Yields from SAS Pristine and SAS Scala are same	0.843	BFR pressures from SAS Pristine and SAS Scala are same	0.212
Yields from SAS Pristine and SAS Fontelis are same	0.303	BFR pressures from SAS Pristine and SAS Fontelis are same	0.555
Yields from SAS Pristine and SAS Luna Privilege are same	0.212	BFR pressures from SAS Pristine and SAS Luna Privilege are same	0.021
Yields from SAS Scala and SAS Fontelis are same	0.036	BFR pressures from SAS Scala and SAS Fontelis are same	0.093
Yields from SAS Scala and SAS Luna Privilege are same	0.036	BFR pressures from SAS Scala and SAS Luna Privilege are same	0.000
Yields from SAS Fontelis and SAS Luna Privilege are same	0.555	BFR pressures from SAS Fontelis and SAS Luna Privilege are same	0.303

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454 Table A2. Kolmogorov–Smirnov tests of yields and Botrytis fruit rot (BFR) pressure from different treatments in 2014-15 (*P*-values
455 for two-sided tests).

Null hypothesis	p-value	Null hypothesis	p-value
Yields from Untreated and Calendar-Std Weekly are same	0.015	BFR pressures from Untreated and Calendar-Std Weekly are same	0.022
Yields from Untreated and SAS Thiram are same	0.009	BFR pressures from Untreated and SAS Thiram are same	0.035
Yields from Untreated and SAS Captevate are same	0.258	BFR pressures from Untreated and SAS Captevate are same	0.001
Yields from Untreated and SAS Switch are same	0.006	BFR pressures from Untreated and SAS Switch are same	0.000
Yields from Untreated and SAS Pristine are same	0.097	BFR pressures from Untreated and SAS Pristine are same	0.035
Yields from Untreated and SAS Scala are same	0.431	BFR pressures from Untreated and SAS Scala are same	0.431
Yields from Untreated and SAS Fontelis are same	0.006	BFR pressures from Untreated and SAS Fontelis are same	0.001

Yields from Untreated and SAS Luna Privilege are same	0.022	BFR pressures from Untreated and SAS Luna Privilege are same	0.000
Yields from Untreated and SAS Thirmam 24/7+Fontelis are same	0.035	BFR pressures from Untreated and SAS Thirmam 24/7+Fontelis are same	0.000
Yields from Calendar-Std Weekly and SAS Thiram 24/7 are same	0.183	BFR pressures from Calendar-Std Weekly and SAS Thiram 24/7 are same	0.867
Yields from Calendar-Std Weekly and SAS Captevate are same	0.145	BFR pressures from Calendar-Std Weekly and SAS Captevate are same	0.322
Yields from Calendar-Std Weekly and SAS Switch are same	0.774	BFR pressures from Calendar-Std Weekly and SAS Switch are same	0.049
Yields from Calendar-Std Weekly and SAS Pristine are same	0.174	BFR pressures from Calendar-Std Weekly and SAS Pristine are same	0.952
Yields from Calendar-Std Weekly and SAS Scala are same	0.097	BFR pressures from Calendar-Std Weekly and SAS Scala are same	0.183
Yields from Calendar-Std Weekly and SAS Fontelis are same	0.145	BFR pressures from Calendar-Std Weekly and SAS Fontelis are same	0.322
Yields from Calendar-Std Weekly and SAS Luna Privilege are same	0.529	BFR pressures from Calendar-Std Weekly and SAS Luna Privilege are same	0.319
Yields from Calendar-Std Weekly and SAS Thirmam 24/7+Fontelis are same	0.431	BFR pressures from Calendar-Std Weekly and SAS Thirmam 24/7+Fontelis are same	0.183
Yields from SAS Thiram 24/7 and SAS Captevate are same	0.322	BFR pressures from SAS Thiram 24/7 and SAS Captevate are same	0.258
Yields from SAS Thiram 24/7 and SAS Switch are same	0.641	BFR pressures from SAS Thiram 24/7 and SAS Switch are same	0.039
Yields from SAS Thiram 24/7 and SAS Pristine are same	0.097	BFR pressures from SAS Thiram 24/7 and SAS Pristine are same	1.000
Yields from SAS Thiram 24/7 and SAS Scala are same	0.049	BFR pressures from SAS Thiram 24/7 and SAS Scala are same	0.258
Yields from SAS Thiram 24/7 and SAS Fontelis are same	0.952	BFR pressures from SAS Thiram 24/7 and SAS Fontelis are same	0.773
Yields from SAS Thiram 24/7 and SAS Luna Privilege are same	0.529	BFR pressures from SAS Thiram 24/7 and SAS Luna Privilege are same	0.183
Yields from SAS Thiram 24/7 and SAS Thirmam	0.529	BFR pressures from SAS Thiram 24/7 and SAS	0.145

24/7+Fontelis are same		Thirmam 24/7+Fontelis are same	
Yields from SAS Captevate and SAS Switch are same	0.258	BFR pressures from SAS Captevate and SAS Switch are same	0.322
Yields from SAS Captevate and SAS Pristine are same	0.985	BFR pressures from SAS Captevate and SAS Pristine are same	0.258
Yields from SAS Captevate and SAS Scala are same	0.952	BFR pressures from SAS Captevate and SAS Scala are same	0.002
Yields from SAS Captevate and SAS Fontelis are same	0.529	BFR pressures from SAS Captevate and SAS Fontelis are same	0.969
Yields from SAS Captevate and SAS Luna Privilege are same	0.258	BFR pressures from SAS Captevate and SAS Luna Privilege are same	0.322
Yields from SAS Captevate and SAS Thirmam 24/7+Fontelis are same	0.529	BFR pressures from SAS Captevate and SAS Thirmam 24/7+Fontelis are same	0.999
Yields from SAS Switch and SAS Pristine are same	0.529	BFR pressures from SAS Switch and SAS Pristine are same	0.039
Yields from SAS Switch and SAS Scala are same	0.258	BFR pressures from SAS Switch and SAS Scala are same	0.001
Yields from SAS Switch and SAS Fontelis are same	0.529	BFR pressures from SAS Switch and SAS Fontelis are same	0.319
Yields from SAS Switch and SAS Luna Privilege are same	0.985	BFR pressures from SAS Switch and SAS Luna Privilege are same	0.867
Yields from SAS Switch and SAS Thirmam 24/7+Fontelis are same	0.773	BFR pressures from SAS Switch and SAS Thirmam 24/7+Fontelis are same	0.322
Yields from SAS Pristine and SAS Scala are same	0.774	BFR pressures from SAS Pristine and SAS Scala are same	0.322
Yields from SAS Pristine and SAS Fontelis are same	0.431	BFR pressures from SAS Pristine and SAS Fontelis are same	0.773
Yields from SAS Pristine and SAS Luna Privilege are same	0.431	BFR pressures from SAS Pristine and SAS Luna Privilege are same	0.174
Yields from SAS Pristine and SAS Thirmam 24/7+Fontelis are same	0.658	BFR pressures from SAS Pristine and SAS Thirmam 24/7+Fontelis are same	0.145
Yields from SAS Scala and SAS Fontelis are same	0.183	BFR pressures from SAS Scala and SAS Fontelis are same	0.049

Yields from SAS Scala and SAS Luna Privilege are same	0.322	BFR pressures from SAS Scala and SAS Luna Privilege are same	0.010
Yields from SAS Scala and SAS Thirmam 24/7+Fontelis are same	0.322	BFR pressures from SAS Scala and SAS Thirmam 24/7+Fontelis are same	0.001
Yields from SAS Fontelis and SAS Luna Privilege are same	0.658	BFR pressures from SAS Fontelis and SAS Luna Privilege are same	0.529
Yields from SAS Fontelis and SAS Thirmam 24/7+Fontelis are same	0.773	BFR pressures from SAS Fontelis and SAS Thirmam 24/7+Fontelis are same	0.773
Yields from SAS Luna Tranquility and SAS Thirmam 24/7+Fontelis are same	0.985	BFR pressures from SAS Luna Tranquility and SAS Thirmam 24/7+Fontelis are same	0.529

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