Evaluating economic threshold for dynamically optimal disease management

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Economic Threshold for Dynamically Optimal Late Blight Management

Abstract

Precision agriculture has emerged as a revolutionary technology in helping make farm decisions. It transforms farm related data into information, and then coverts information into useful knowledge for decision-making. This study evaluates economic thresholds for a new web-based decision support system developed for precision fungicide management for potato production. Using 10 years of computer simulation experiments from 152 locations in the United States, we compared different thresholds in terms of disease severity, fungicide usage efficiency, and net income over fungicide cost to manage potato late blight disease. The empirical results show that the economic thresholds improved disease suppression and farming profit relative to the previous critical thresholds while maintaining fungicide use efficiency.

Key Words: Economic threshold, stochastic optimization, precision farming, disease management, late blight

Introduction

Precision agriculture relies on information systems to optimize agricultural production decisions by accounting for variability and uncertainties (Gebbers and Adamchuk 2010). It identifies site-specific differences within fields and adjusts management actions accordingly (Auernhammer 2001; Schimmelpfennig and Ebel 2011). Based on information provided, growers can make informed farm decisions (e.g. planting, harvesting, crop protection) using limited farm resources (Cooke et al. 2011; Lowenberg-DeBoer 2015). The majority of precision agriculture studies focus on corn, soybeans, and other major cereal crops, whereas vegetable crops have historically received less attention (Griffin and Lowenberg-DeBoer 2005). Few studies examine the precision agriculture for potato production.

Potatoes are the fourth largest crop in the world, surpassed by maize, wheat, and rice (FAO 2009). The United States is among the world's largest potato producing countries (FAO 2016), with the value of all potatoes sold at $3.66 billion and harvested acres at 1.05 million in 2014 (USDA 2015). As technology continues to evolve, new potential applications of precision agriculture are becoming possible. These include tying forecasts of weather to crop protection strategies in controlling late blight disease on potato and tomato plants (Small, Joseph, and Fry 2015a). Of all potato diseases, late blight, caused by the *Phytophthora infestans* (Mont.) de Bary, may be the most economically damaging pathogen (Niederhauser and Mills 1953; Fry and Goodwin 1997; Guenthner et al. 1999; Wale, Platt, and N. 2008; Johnson 2008). In the U.S., the annual cost of late blight to potato production is estimated to be $287.8 million, of which fungicide costs consist of a substantial proportion (Guenthner, Michael, and Nolte 2001). Worldwide, a conservative estimate of the annual cost of the disease to potato production is $6.7 billion in yield losses and costs of late blight control measures (Haverkort et al. 2008).

The most prevalent means of late blight control in modern agriculture is the preventive use of fungicide. However, fungicide use remains a source of much debate concerning environmental pollution and food safety issues. In addition, the use of fungicides raises the cost of farming and can simultaneously lead to the emergence of more virulent late blight strains with high fungicide resistance (Fry, Bruck, and Mundt 1979; Deahl et al. 1991; Deahl, Inglis, and Demuth 1993; Goodwin, Sujkowski, and Fry 1996). An alternative method of late blight control relies on the use of precision farming technology, named BlightPro decision support system (DSS) (Small, Joseph, and Fry 2015a). It recommends precise and timely use of fungicide in accordance with weather conditions, pathogen inoculum, host resistance, as well as fungicide characteristics and efficacy (Small, Joseph, and Fry 2015a). The use of precision farming technology as a guidance for fungicide application to manage late blight mitigates production risk, improves potato farming efficiency, and reduces the environmental impact of fungicide usage (Small, Joseph, and Fry 2015b; Liu et al. 2015).

Liu et al. (2015) evaluated the economic benefits of scheduling fungicide applications with DSS. The results showed that economic benefits to potato growers of adopting the precision agriculture technology ranged from $30 to $544 per acre (Liu et al. 2015). The version of DSS evaluated by Liu et al. (2015) schedules fungicide applications based on the thresholds obtained from field experiments. The system neglects the economic cost and benefit in control of the disease and thus the recommended fungicide applications may not be economically optimal. This research introduces economic aspects into the current Decision Support System, and evaluates different thresholds in the late blight decision support system. We obtain the optimal thresholds in terms of disease severity, fungicide usage efficiency, and net income over fungicide cost to manage potato late blight disease.

BlightPro Decision Support System

Late blight poses a special challenge for potato growers in humid (Olanya et al. 2007) and cool (16-21 °C) climates (Wallin 1962; Krause, Massie, and Hyre 1975). If not controlled properly, the disease has the potential to completely destroy the entire field within 2-3 weeks after the first visible symptoms appear (Johnson 2008). Unexpected infection can cause significant crop losses and economic failure rapidly, which creates tremendous financial stress to potato growers (Fry and Goodwin 1997). Late blight can be dispersed up to a 30 mile radius by wind, rain splash, or water (Goodwin et al. 1994), and can spread long distances through infected potato tubers, tomatoes and tomato seeds (Goodwin et al. 1994; Fry and Goodwin 1997). The complexity in decision making for disease management creates an opportunity for precision farming technology to provide scientific-based information as a guidance in decision making (Small, Joseph, and Fry 2015b).

The BlightPro decision support system (DSS) is an an internet-based platform and avaiable at the USAblight website (www.usablight.org) (Small, Joseph, and Fry 2015a, 2015b). The primary objective of the DSS is to to utilize location-specific weather data to drive disease forecasts for late blight, and provide real-time support for late blight management in the US (Small, Joseph, and Fry 2015a). DSS was developed by Cornell University researchers to increase the in-season precision of fungicide application by utilizing location-specific weather information, and provide real-time support for late blight management (Small, Joseph, and Fry 2015a). DSS links several models (Krause, Massie, and Hyre 1975; Fry, Apple, and Bruhn 1983; Andrade-Piedra et al. 2005a) into a system that enables predictions of disease dynamics based on weather conditions, host resistance, pathogen inoculum, and fungicide use. An integrated alert system in DSS issues notications about the upcoming critical thresholds for intervetion (fungicide applications) via e-mail and/or text message, when weather conditions are favorable.

Figure 1 illustrates the method of application for the DSS-recommended spray schedule. The timing of the fungicide application for the DSS-recommended spray schedule is based on wet period duration and average temperature during each wet period, as well as daily precipitation/irrigation (Small, Joseph, and Fry 2015a). Three major systems are enbedded into DSS (Small, Joseph, and Fry 2015a), including late blight disese simulator system, and two late blight forecasting systems: Blitecast and Simcast (Figure 2). Using the Blitecast forecasting system (Krause, Massie, and Hyre 1975), a user might schedule his/her initial fungicide appliation based on the accumulation of a Blitecast severity value of 18. Then, the user can swith to Simcast to schedule subsequenct fungicide applications using Simcast thresholds. Simcast integrates the effect of host resistance, prevailing weather on late blight progress, and prevailing weather on fungicide application (Fry, Apple, and Bruhn 1983). The Simcast forecast system functions by calculating blight units and fungicide units, which reflect the influence of prevailing weather on the disease and fungicide residue, respectively (Fry, Apple, and Bruhn 1983). If the daily accumulated blight units or fungicide units reach a critical threshold a fungicide application is recommended to the user.

This paper evaluates the use of economic thresholds in the late blight decision support system. The thresholds evaluated in this paper are the thresholds from the Simcast system. Simcast thresholds (Blight Unit and Fungicide Unit) were established based on field experiemnts (Small, Joseph, and Fry 2015a). Under some circumstances, results with the DSS schedules for moderately susceptible crops did not achieve sufficient disease suppression (Small, Joseph, and

Fry 2015b). Moreover, the system neglects the economic cost and benefit of additional applications to control the disease. Thus, the current Blight Unit and Fungicide Unit thresholds in the Simcast system may not be economically optimal (see Table 1 for current thresholds). We evaluated different Blight Unit and Fungicide Unit thresholds in the Simcast system to obtain the optimal economic threshold for managing late blight disease.

Data

Many researchers have used computer simulation models to evaluate other alternative farming practices, including integrated pest management strategies for turnip greens, corn, and peas (Musser, Tew, and Epperson 1981), multi-species insect management strategies on soybeans (Boggess, Cardelli, and Barfield 1985), and soybean aphid management using natural enemies (Zhang and Swinton 2009). In this paper, computer simulation experiments were conducted at Fry Lab at Cornell University to generate the data for number of fungicide applications, disease rating (AUDPC[2]), and potato yield loss percentage (Small, Joseph, and Fry 2015b). The LATEBLIGHT 2004 disease model integrated with fungicide sub-models (Andrade-Piedra et al. 2005a) was used in conjunction with the potato yield loss model (Shtienberg et al. 1990) to evaluate fungicide scheduling methods. These models have been widely tested and validated to simulate late blight disease progress (Rakotonindraina et al. 2012) and the yield loss percentage caused by the disease (Andrade-Piedra et al. 2005b).

We use computer simulation programs for various critical threshold combinations. Our analysis integrates different models covering DSS, pathology models, and economic components. We use the thresholds of DSS Simcast System (blight units and fungicide units),

[2] AUDPC is area under the disease progress curve, which is a quantitative summary of disease intensity over time, for comparison across years, locations, or management tactics.

the LATEBLIGHT simulation model (Andrade-Piedra, Hijmans, Juarez, et al. 2005), and the yield model (Shtienberg et al. 1990) to schedule fungicide applications. Different combinations of blight unit and fungicide unit thresholds achieve different net income over fungicide cost (revenue of potato minus the cost of fungicide application). Weather plays a significant role in determining potato late blight disease and potato yield. The model used in this paper not only considers the dynamic decision making process, but also considers the influence of weather on late blight disease incidence and severity, and potato yield.

Computer simulations experiments were generated at Fry Lab at Cornell University, using 10 years of meteorological data (2005-2014), obtained from the Northeast Regional Climate Center. 152 locations were examined from 5 major potato producing states (Maine, Massachusetts, New York, North Dakota, and Wisconsin). Only locations and years with less than 2% missing weather data between the date of emergence and vine kill were used. This criterion resulted in 919 environments with suitable weather data. The simulation experiments were generated for three levels of disease resistant potato cultivars: susceptible, moderately susceptible, and moderately resistant cultivars. The simulations started 6 days after the Blitecast threshold reached a severity value of 18.

Figure 3 shows the simulation process for 152 locations from 2005 to 2014. We investigated different combinations of blight unit and fungicide unit critical thresholds in order to select the optimal combination. The number of combinations of thresholds for susceptible, moderately susceptible, and moderately resistant were 208, 176, and 30, respectively. Simulations were also generated for two additional methods of fungicide application throughout production season: the calendar based (the 7-day spray schedule) method and a control (no fungicide application). In total; 388,764 simulations (919 environment × three resistant levels ×

three method of fungicide application) were used to compare the DSS recommended spray schedule with the traditional calendar spray schedule.

The following common parameters were used (Small, Joseph, and Fry 2015b). The length of the season was 110 days. Late blight was initiated with 0.001% disease severity (one lesion per 10 plants). A protectant fungicide, Bravo WeatherStik (active ingredient chlorothalonil), was applied at a rate of 1.5 pints per acre for each application (equivalent to 1.34 kg a.i./ha). We have limited our study to rain fed regions and temperate climates where the cold winter eliminates host plants between growing seasons (Small, Joseph, and Fry 2015b). For a comprehensive description of the reason for the elimination of locations see Small, Joseph, and Fry (2015b). All diseases other than late blight and the effects of pests, weeds, nutrients, and heat or frost shock were not modelled. Growers are assumed to be able to initiate fungicide applications according to the DSS-based strategy. We did not attempt to estimate the loss due to tuber infections, only yield loss at harvest was considered.

Method

Potato yield was estimated using potato yield loss percentage from the computer simulation results and historical state-level average potato yield data obtained from the USDA Potatoes Annual Summary. Specifically, the potato yield is calculated for each production season y, each state s, and each location l as follows:

$$\boldsymbol{Potato\ yield_{l,y}} = average\ potato\ yield_{s,y} * \left(1 - \frac{yield\ loss\ percentage_{l,y}}{100}\right) \quad (1)$$

Table 2 shows the fungicide application cost per acre for each application in 2013. We assumed that the fungicide cost and application cost were the same for all 152 locations. USDA Prices Paid Indices (agricultural chemical and machinery indices) are used to adjust the fungicide price and application cost in 2013 to nominal prices in previous years. In turn, cost of fungicide applications were calculated as a product of fungicide application cost and number of fungicide applications:

$$\boldsymbol{Cost\ of\ fungicide\ applications}_{l,y} = \left(Fungicide\ cost_y + application\ cost_y\right) * no.of\ application_{l,y} \quad (2)$$

Historical state-level potato price data was obtained from the USDA Potatoes Annual Summary. Average yield and price were assumed to be the same among different disease-resistant potato groups. Revenue is calculated for each production season and each location as a product of yield and price:

$$\boldsymbol{Revenue}_{l,y} = Potato\ price_{l,y} * Potato\ yield_{l,y} \quad (3)$$

For each production season and each location, net income over fungicide cost was equal to cost of fungicide applications subtracted from revenue:

$$\boldsymbol{Net\ income\ over\ fungicide\ cost}_{l,y} = Revenue_{l,y} - Cost\ of\ fungicide\ applications_{l,y} \quad (4)$$

The optimal combination was selected based on the average AUDPC, fungicide use efficiency, and net income for the threshold combination over 10 years and 152 locations.

Results

Susceptible Cultivars

Table 3, Table 4, and Table 5 report the average disease severity (AUDPC), fungicide efficiency, and net income for susceptible cultivars. We investigated 208 different combinations of blight unit and fungicide unit critical thresholds in order to select the optimal combination. Average AUDPC ranges from 61 to 1774 and average AUDPC for previous threshold (30 Blight Unit and -15 Fungicide Unit) in the system is 339. The best disease suppression threshold is achieved at 25 Blight Unit and -13 Fungicide Unit. Average fungicide use efficiency ranges from 6.3 to 7.6 and average fungicide use efficiency for previous threshold in the system is 7.1. The best fungicide use efficiency threshold is achieved at 40 Blight Unit and -16 Fungicide Unit. Average net income ranges from $3,053/Acre to $3,170/Acre and average net income for previous threshold in the system is $3,158. The best net income threshold is achieved at 40 Blight Unit and -13 Fungicide Unit.

The optimal threshold combination was selected based on the average AUDPC, fungicide use efficiency and net income. We constructed contour graphs of average AUDPC (Figure 4), average fungicide use efficiency (Figure 5), and net income (Figure 6) in order to determine the blight unit and fungicide unit combination that resulted in a lower AUDPC while maintaining fungicide use efficiency and net income, relative to the results for the previous critical thresholds. The new optimal combination of critical thresholds we selected for susceptible cultivars is 40 Blight Unit and -13 Fungicide Unit. This modification improved disease suppression by 15% relative to the previous critical thresholds and the fungicide use efficiency by 7%.

<u>Moderately Susceptible Cultivars</u>

Table 6, Table 7, and Table 8 reports the average disease severity (AUDPC), fungicide efficiency, and net income for moderately susceptible cultivars. We investigated 176 different combinations of blight unit and fungicide unit critical thresholds in order to select the optimal combination. Average AUDPC ranges from 142 to 1847, and average AUDPC for previous threshold (35 Blight Unit and -20 Fungicide Unit) in the system is 1035. The best disease suppression threshold was achieved at 25 Blight Unit and -15 Fungicide Unit. Average fungicide use efficiency ranges from 7.7 to 8.9, and average fungicide use efficiency for previous threshold in the system is 8.8. The best fungicide use efficiency threshold is achieved at 40

Blight Unit and -17 Fungicide Unit. Average net income ranged from $3,090/Acre to $3,199/Acre, and average net income for previous threshold in the system is $3,166/Acre. The best net income threshold was achieved at 40 Blight Unit and -15 Fungicide Unit.

The optimal threshold combination was selected based on the average AUDPC, fungicide use efficiency, and net income. We constructed contour graphs of average AUDPC (Figure 7), average fungicide use efficiency (Figure 8), and net income (Figure 9) in order to determine the blight unit and fungicide unit combination that resulted in a lower AUDPC while maintaining fungicide use efficiency and net income, relative to the results for the previous critical thresholds. The new optimal combination of critical thresholds we selected for moderately susceptible cultivars is 40 Blight Unit and -16 Fungicide Unit. This modification improved disease suppression by 49% relative to the previous critical thresholds while maintaining fungicide use efficiency.

Moderately Resistant Cultivars

Table 9, Table 10, and Table 11 report the average disease severity (AUDPC), fungicide efficiency, and net income for moderately resistant cultivars. We investigated 30 different combinations of blight unit and fungicide unit critical thresholds in order to select the optimal combination. Average AUDPC ranged from 114 to 323, and average AUDPC for previous threshold (40 Blight Unit and -25 Fungicide Unit) in the system was 178. The best disease suppression threshold was achieved at 39 Blight Unit and -23 Fungicide Unit. Average fungicide use efficiency ranged from 12.6 to 13.5, and average fungicide use efficiency for previous threshold in the system was 13.2. The best fungicide use efficiency threshold was achieved at 43 Blight Unit and – 28 Fungicide Unit. Average net income ranged from $3,259/Acre to $3,269/Acre and average net income for previous threshold in the system was

$3,264/Acre. The best net income threshold was achieved at 43 Blight Unit and -28 Fungicide Unit.

The optimal threshold combination was selected based on the average AUDPC, fungicide use efficiency, and net income. We constructed contour graphs of average AUDPC (Figure 10), average fungicide use efficiency (Figure 11), and net income (Figure 12) in order to determine the blight unit and fungicide unit combination that resulted in a lower AUDPC while maintaining fungicide use efficiency and net income, relative to the results for the previous critical thresholds. We could not find a new optimal combination of critical thresholds which result in a lower AUDPC while maintaining fungicide use efficiency and net income, relative to the results for the previous critical thresholds. Thus, the previous critical thresholds are already at the optimum.

State Specific Thresholds

Further analyses of the results among different states shows that there are spatial variation for the optimal threshold among different states. Figure 13, Figure 14, and Figure 15 shows the optimal threshold combinations for susceptible cultivars in Massachusetts. The optimal thresholds in Massachusetts are 37 for Blight Unite and -13 for Fungicide Unit, which is different from the optimal threshold for the whole data set at 25 Blight Unit and -13 Fungicide Unit. Variation among other states was also observed.

Summary and Conclusion

This study evaluates the economic thresholds in the late blight decision support system. We introduced economic factors for further improvement of the current DSS. This model allows us to evaluate different combinations of thresholds to obtain the optimal economic thresholds for disease control. Results have been generated using 10 years of historical weather conditions

(2005-2014) in 152 locations (5 states including: MA, ME, ND, NY, WI). Results for three potato cultivar resistance levels for late blight (susceptible, moderately susceptible and moderately resistant) was obtained.

The new optimal combination of critical thresholds we selected are 40 Blight Unit and -13 Fungicide Unit for susceptible cultivars, 40 Blight Unit and -16 Fungicide Unit for moderately susceptible cultivar. The previous critical thresholds for moderately resistant cultivars (40 Blight Unit and -25 Fungicide Unit) also represented the economic optimum For susceptible cultivars, disease suppression was improved by 15% relative to the previous critical thresholds, and fungicide use efficiency was improved by 7%. For moderately susceptible cultivars, disease suppression was improved by 49% relative to the previous critical thresholds while fungicide use efficiency was maintained.

Future research will investigate the spatial differences among different locations in the optimal combinations of thresholds. Precision farming technology is critical to increasing agricultural efficiency and productivity. Our research improves the current precision farming technology in order to achieve higher efficiency in agriculture production. Incorporating economic thresholds into the DSS will help improve late blight management actions taken by potato growers to control the spread of the disease and limit potential loss.

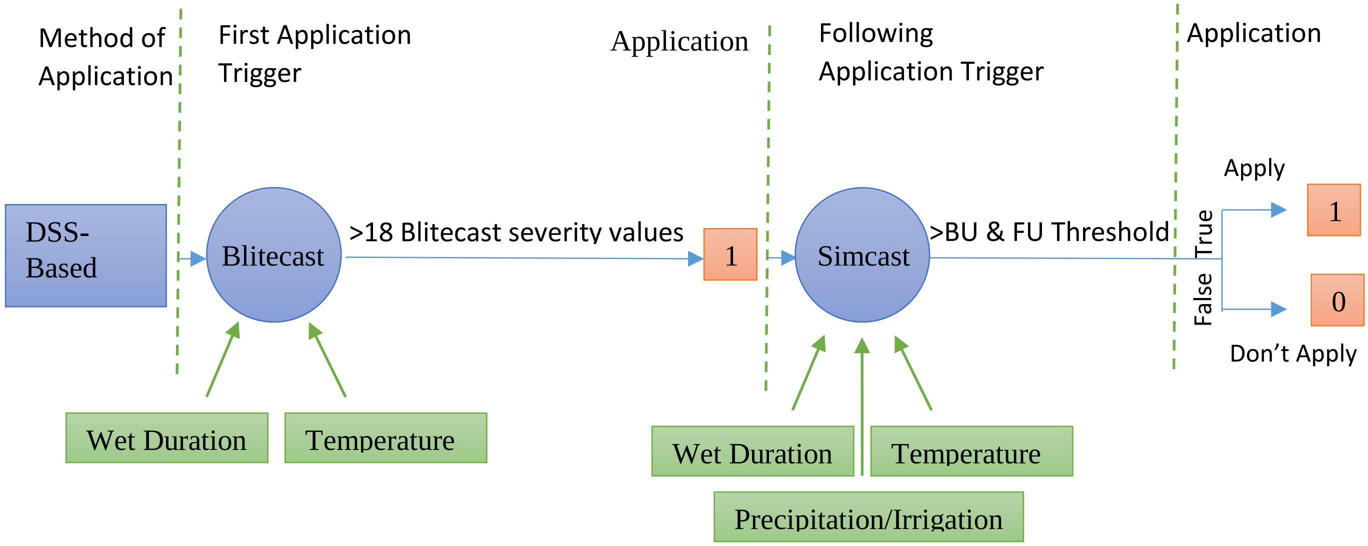

Figure 1. The method of application of the DSS-recommended spray schedule. The Blitecast system reports daily severity values, which are calculated based on web period duration and average temperature during each wet period. The Simcast system reports Blight Unit and Fungicide Unit thresholds, which are calculated based on wet period duration and average temperature during each wet period, as well as daily precipitation/irrigation.

Blitecast Severity Value Status

Date	6/9	6/10	6/11	6/12	6/13	6/14	6/15
Severity Value	16	18	18	18	19	20	20

Key	
	below threshold
>=18	equal to or above threshold

Blight Units and Fungicide Units

Date	06/10	06/11	06/12	06/13	06/14	06/15	06/16
Blight Units	5	11	18	25	25	25	30
Fungicide Units	-1	-5	-10	-14	-15	-16	-17

Key	
	Below threshold.
>=30	Blight unit threshold exceeded.
<=-15	Fungicide unit threshold exceeded.
	Both blight and fungicide unit thresholds exceeded.

Figure 2. Disease forecast reports, Blitecast Summary (left), Simcast Summary (right).

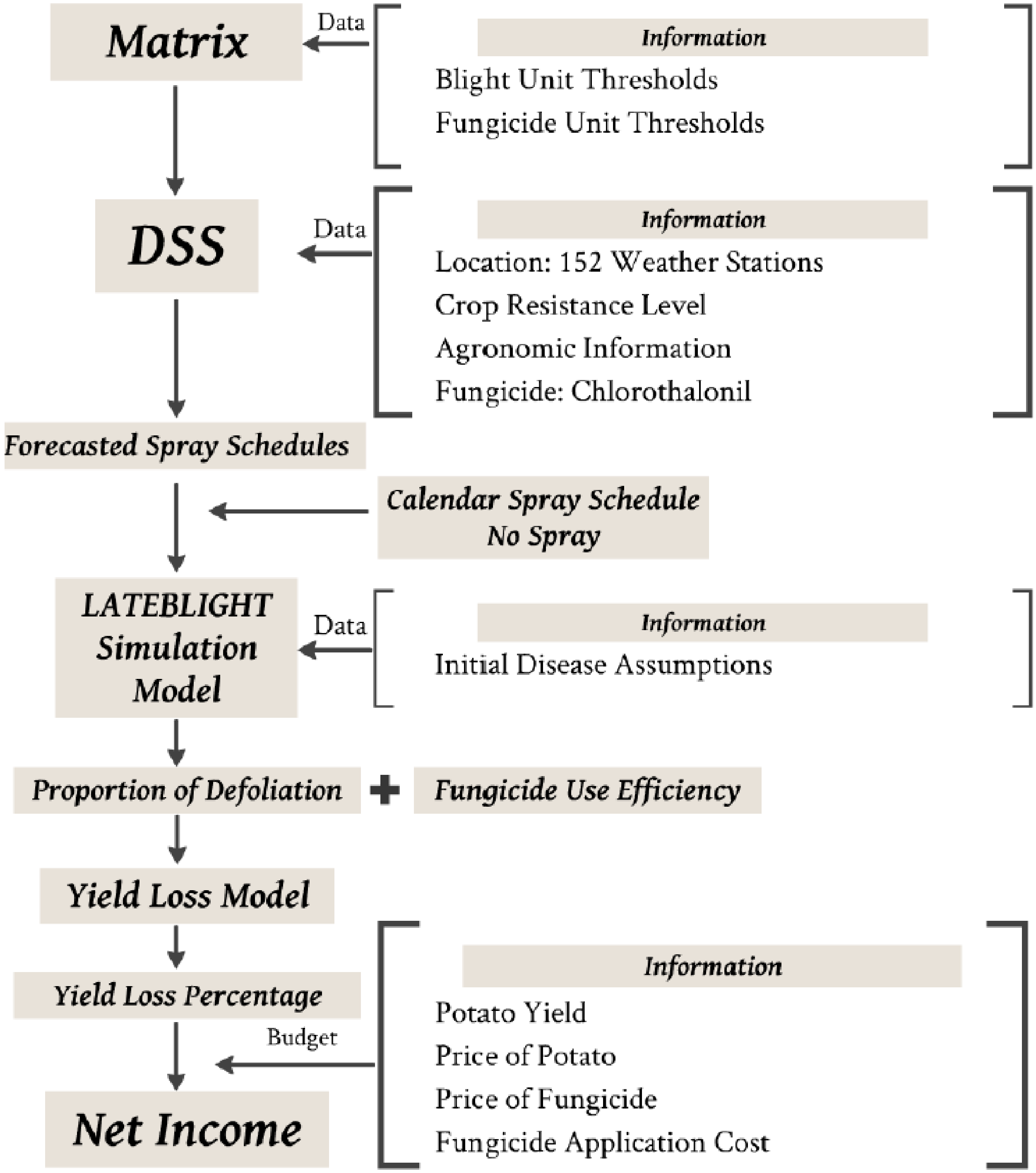

Figure 3. Simulation process for 152 locations from 2005 to 2014. The simulation experiments were generated for three levels of disease resistant potato cultivars: susceptible, moderately susceptible, and moderately resistant cultivars.

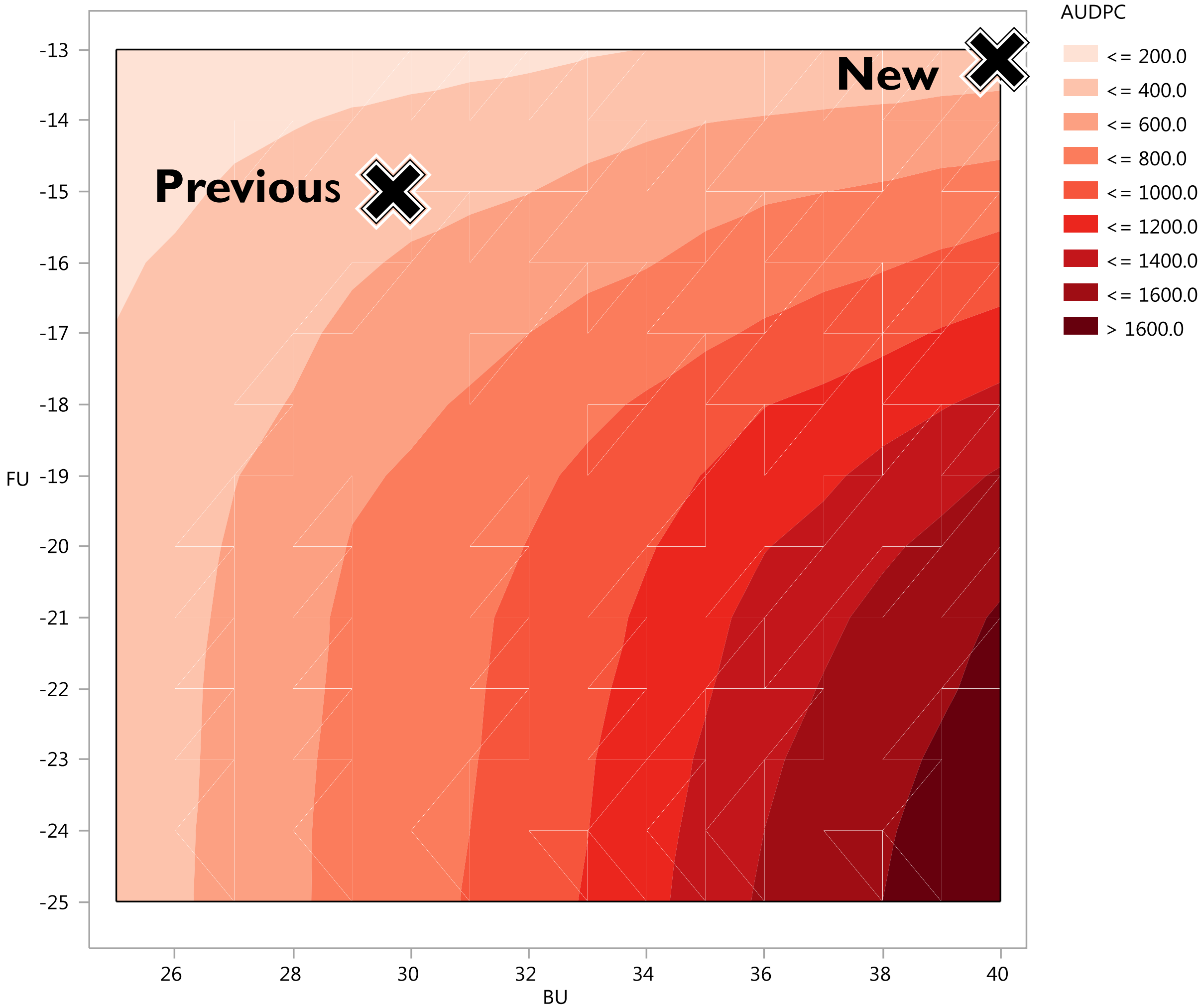

Figure 4. Contour plot of Area Under Disease Progress Curve (AUDPC) for combinations of critical blight unit and fungicide unit thresholds for susceptible cultivars. The X indicates either the previous combination of critical thresholds or the new combination of critical thresholds.

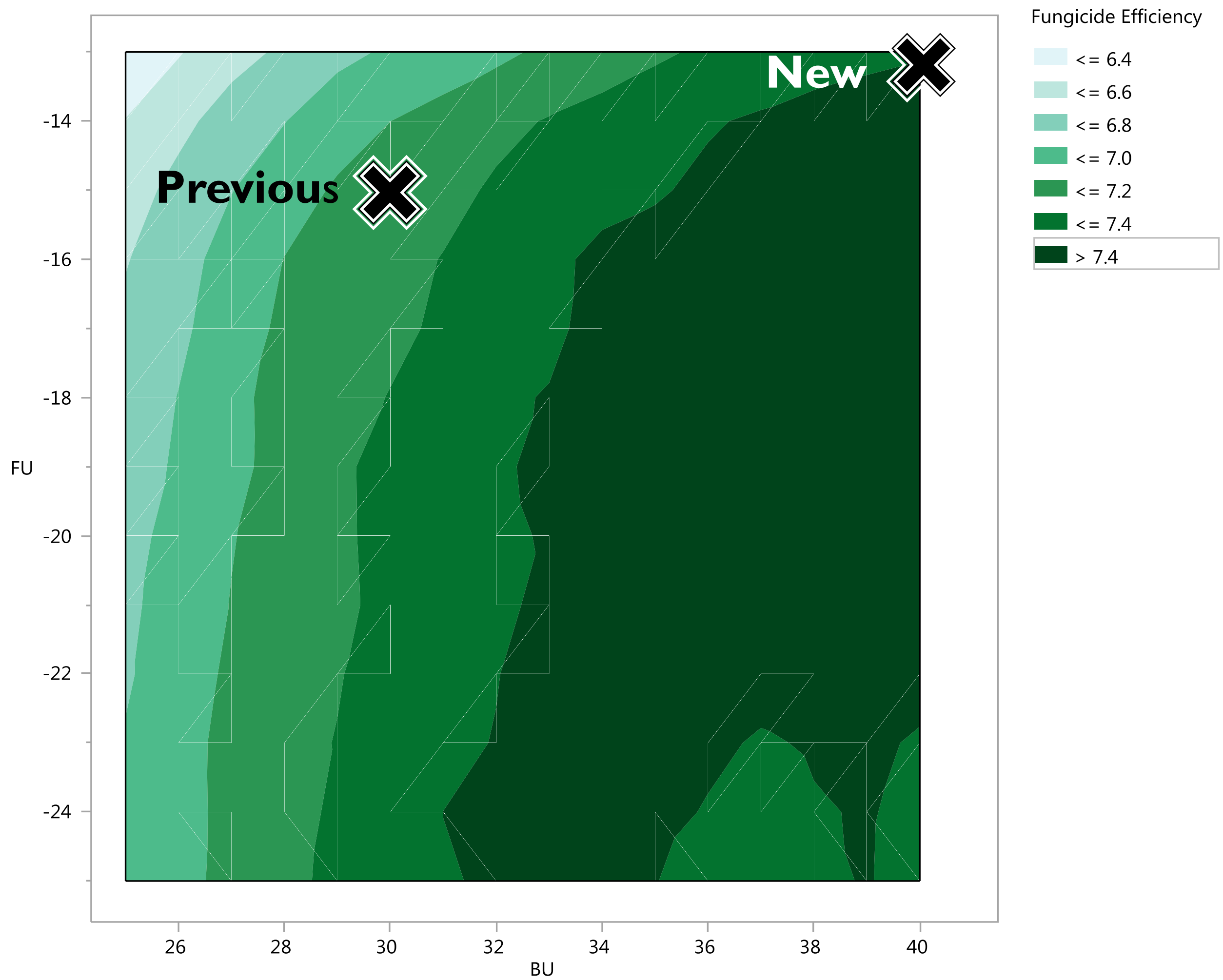

Figure 5. Contour plot of fungicide use efficiency for combinations of critical blight unit and fungicide unit thresholds for susceptible cultivars. The X indicates either the previous combination of critical thresholds or the new combination of critical thresholds.

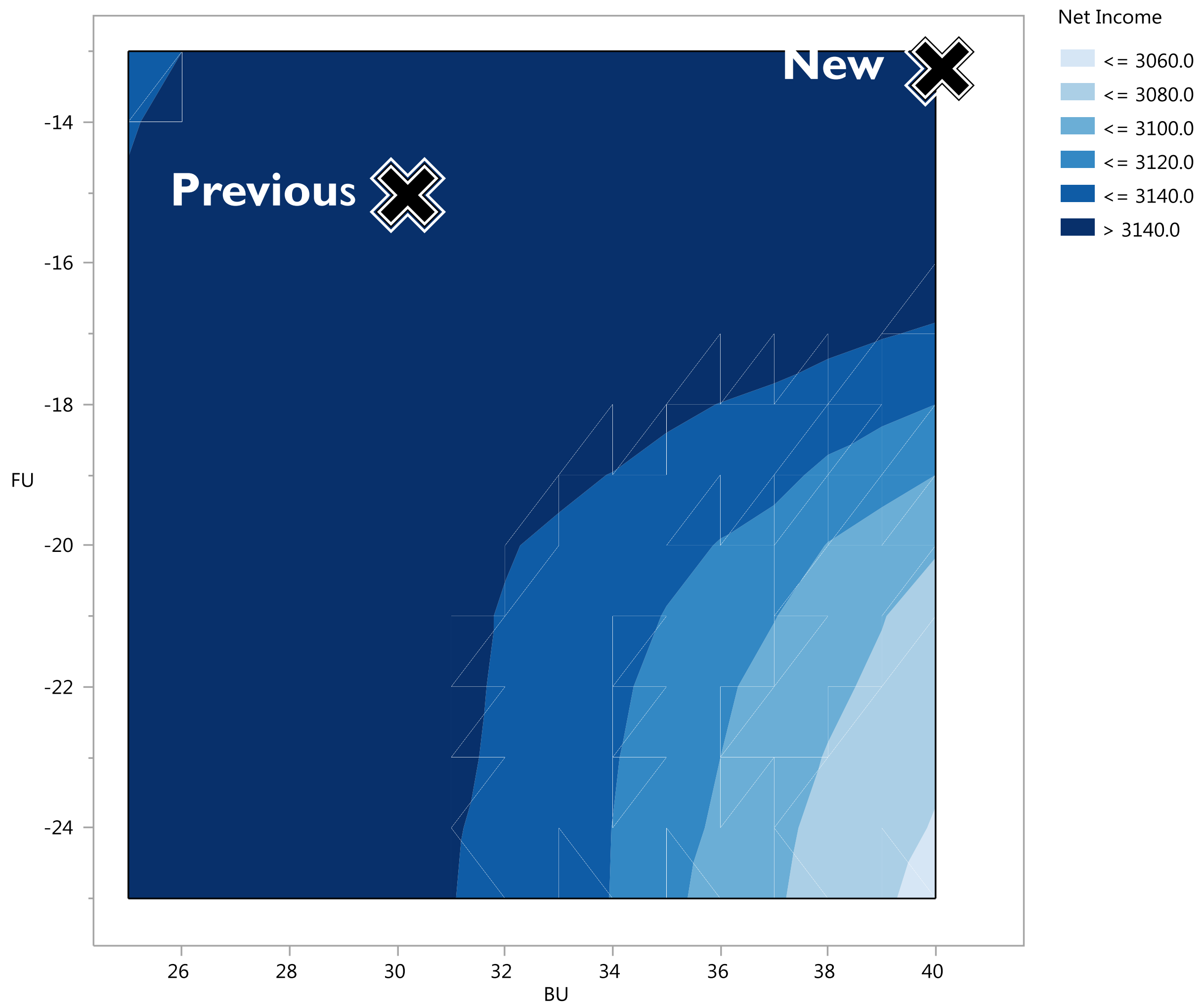

Figure 6. Contour plot of net income for combinations of critical blight unit and fungicide unit thresholds for susceptible cultivars. The X indicates either the previous combination of critical thresholds or the new combination of critical thresholds.

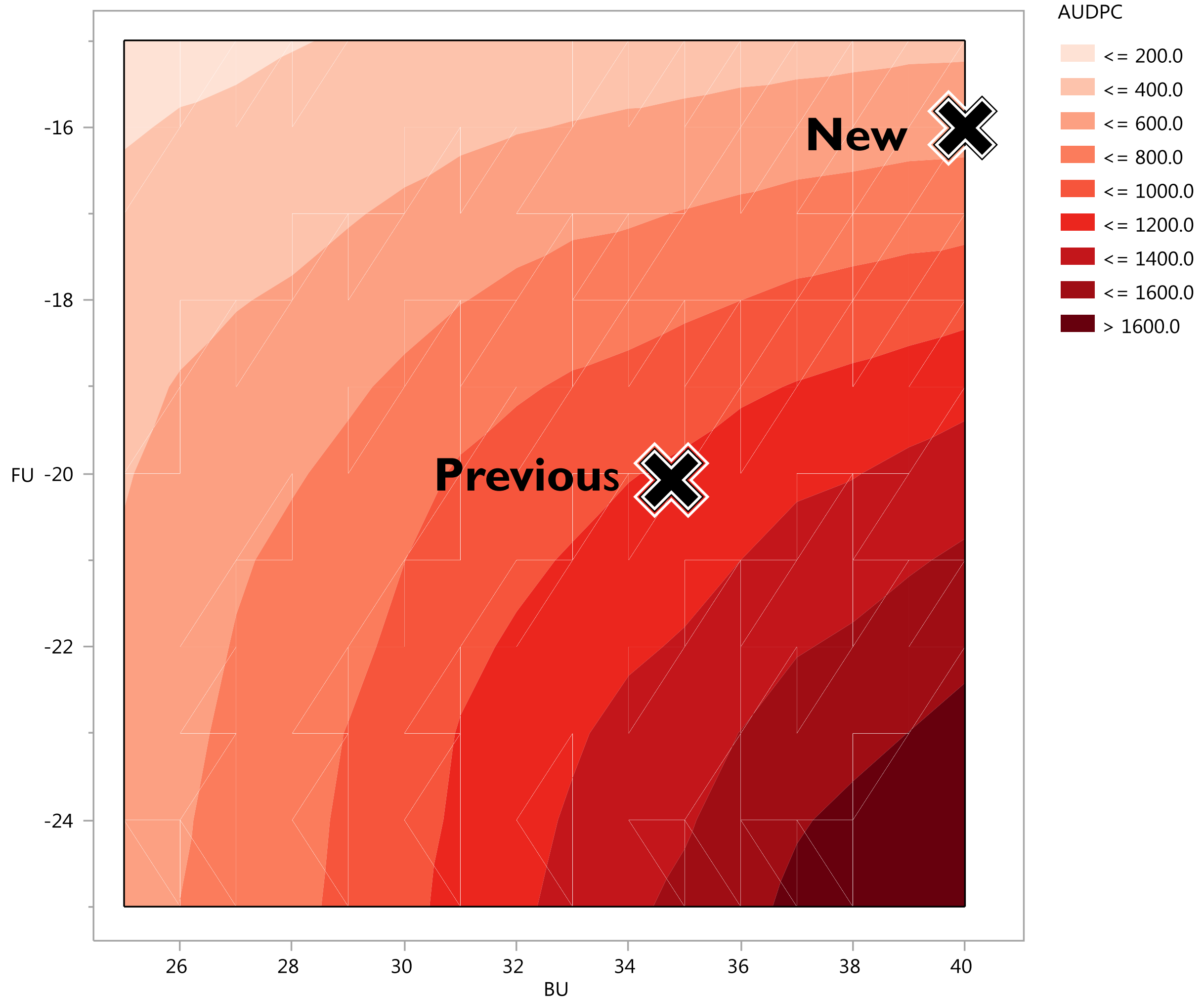

Figure 7. Contour plot of Area Under Disease Progress Curve (AUDPC) for combinations of critical blight unit and fungicide unit thresholds for moderately susceptible cultivars. The X indicates either the previous combination of critical thresholds or the new combination of critical thresholds.

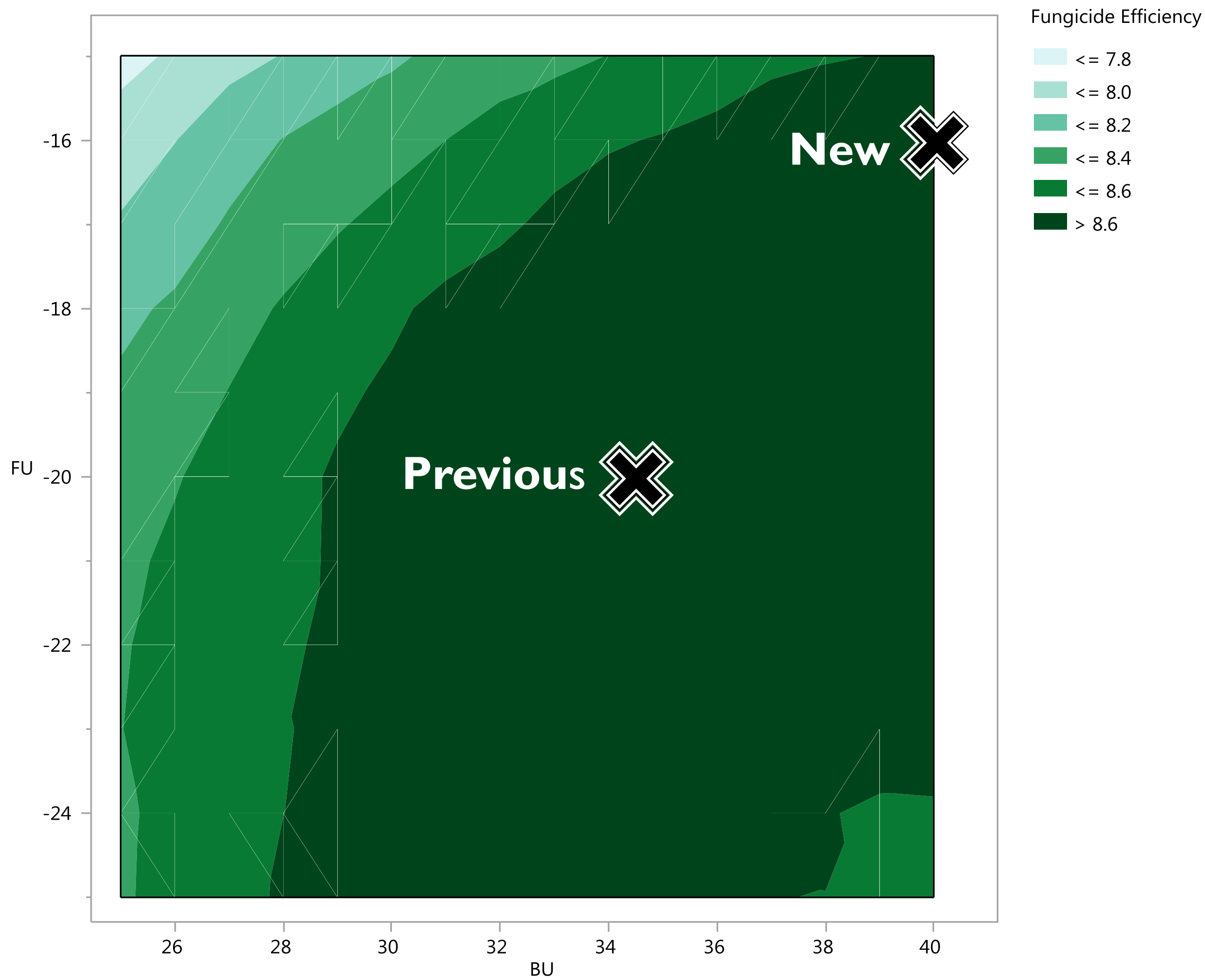

Figure 8. Contour plot of fungicide use efficiency for combinations of critical blight unit and fungicide unit thresholds for moderately susceptible cultivars. The X indicates either the previous combination of critical thresholds or the new combination of critical thresholds.

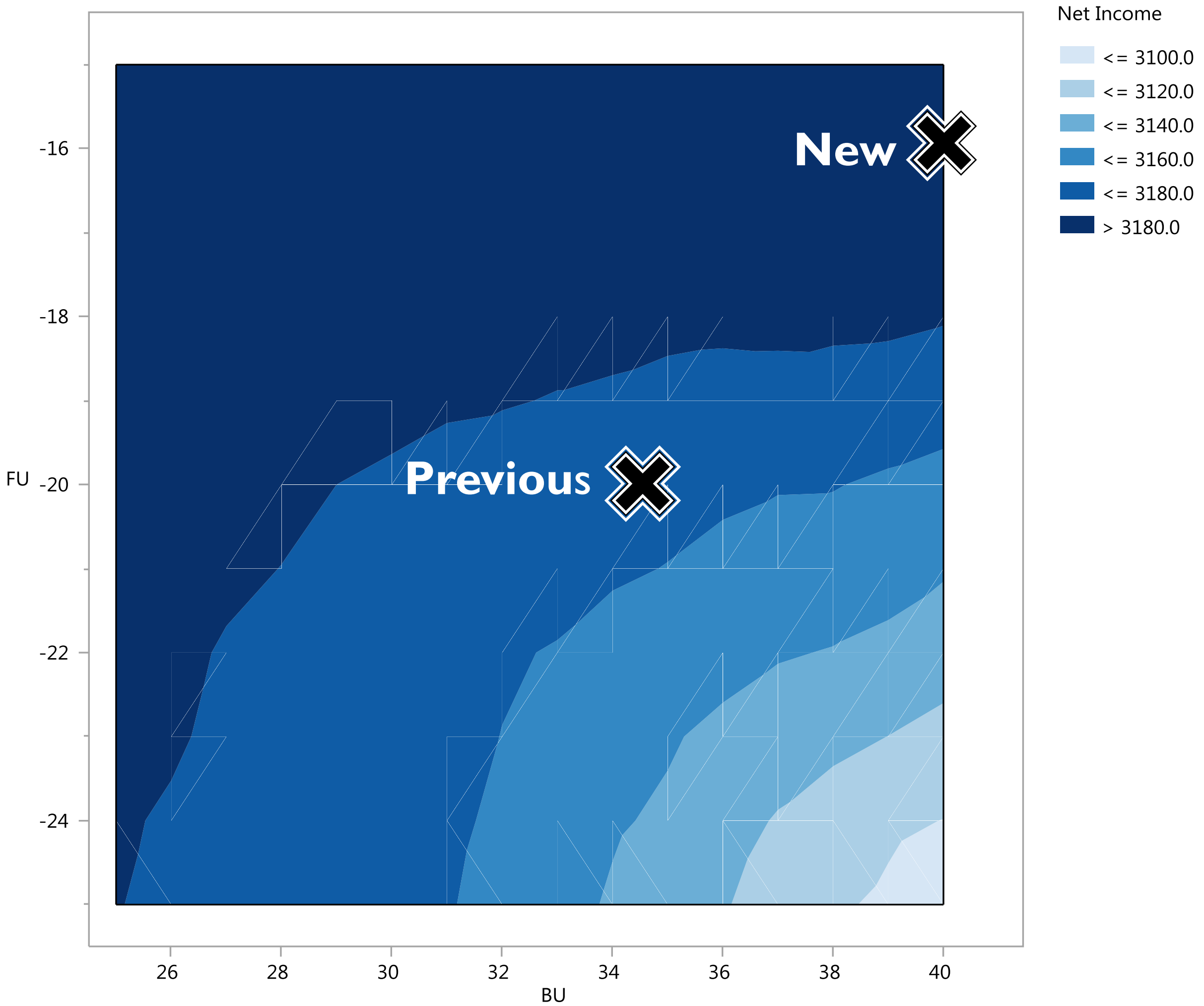

Figure 9. Contour plot of net income for combinations of critical blight unit and fungicide unit thresholds for moderately susceptible cultivars. The X indicates either the previous combination of critical thresholds or the new combination of critical thresholds.

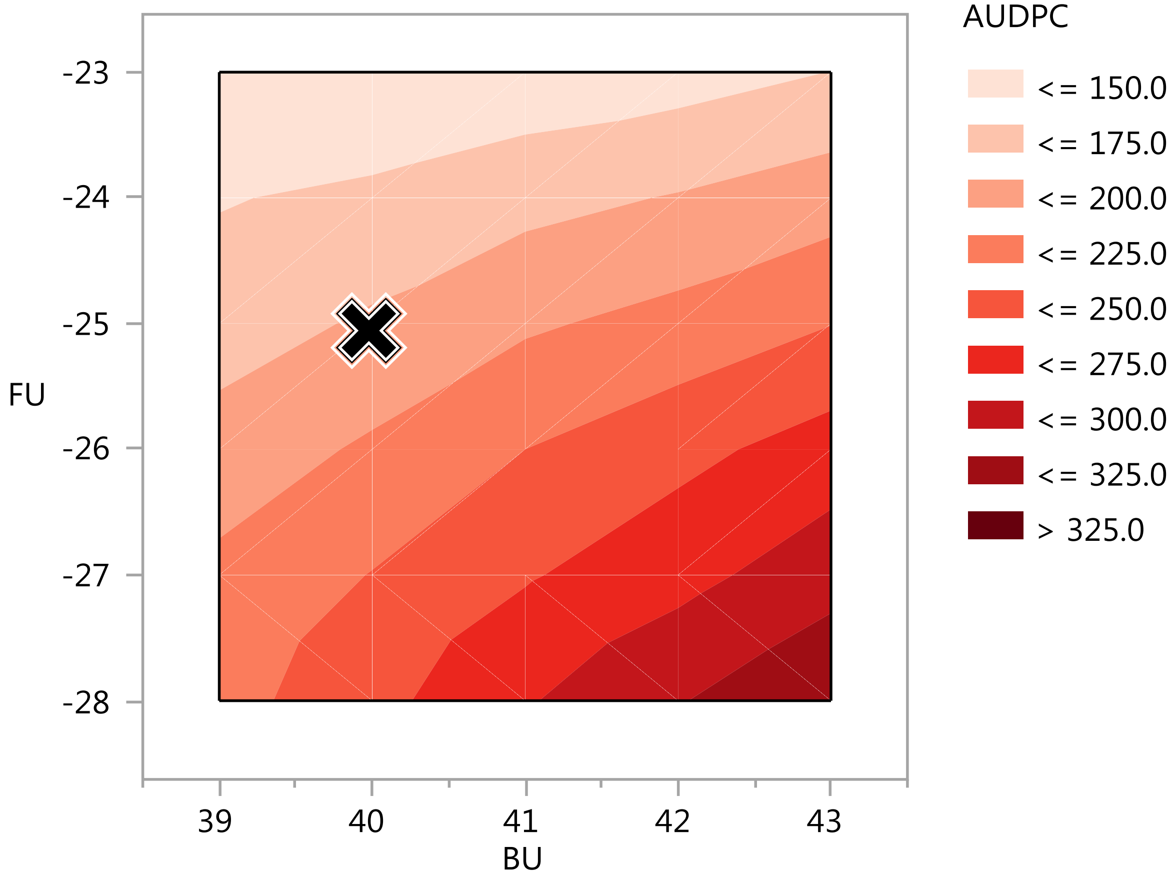

Figure 10. Contour plot of Area Under Disease Progress Curve (AUDPC) for combinations of critical blight unit and fungicide unit thresholds for moderately resistant cultivars. The X indicates the combination of critical thresholds.

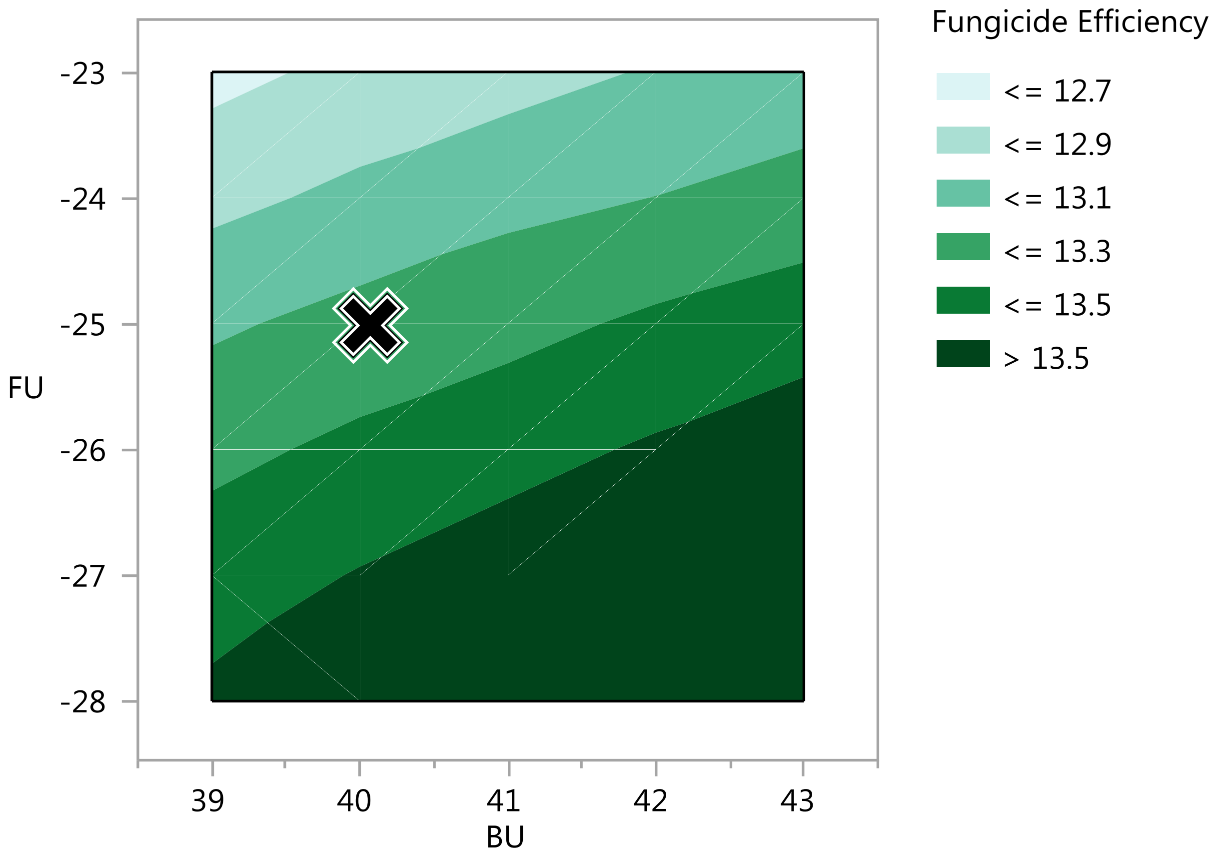

Figure 11. Contour plot of fungicide use efficiency for combinations of critical blight unit and fungicide unit thresholds for moderately resistant cultivars. The X indicates the combination of critical thresholds.

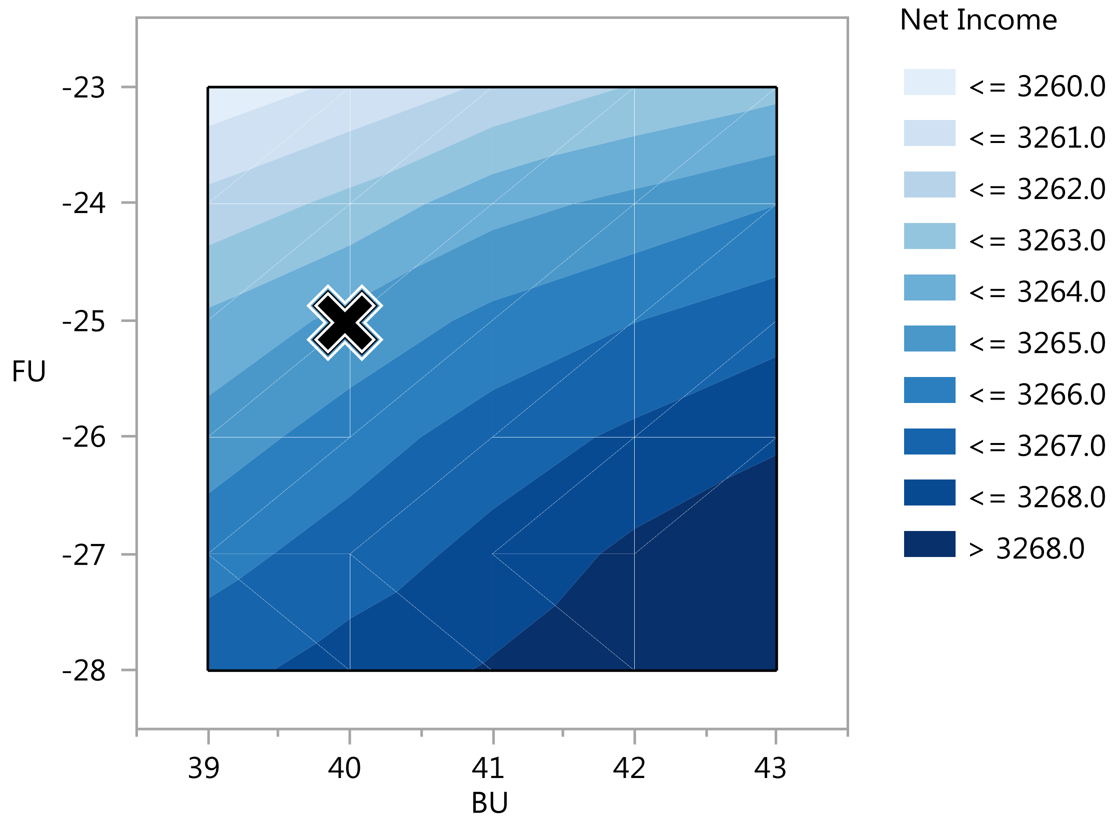

Figure 12. Contour plot of net income for combinations of critical blight unit and fungicide unit thresholds for moderately resistant cultivars. The X indicates the combination of critical thresholds.

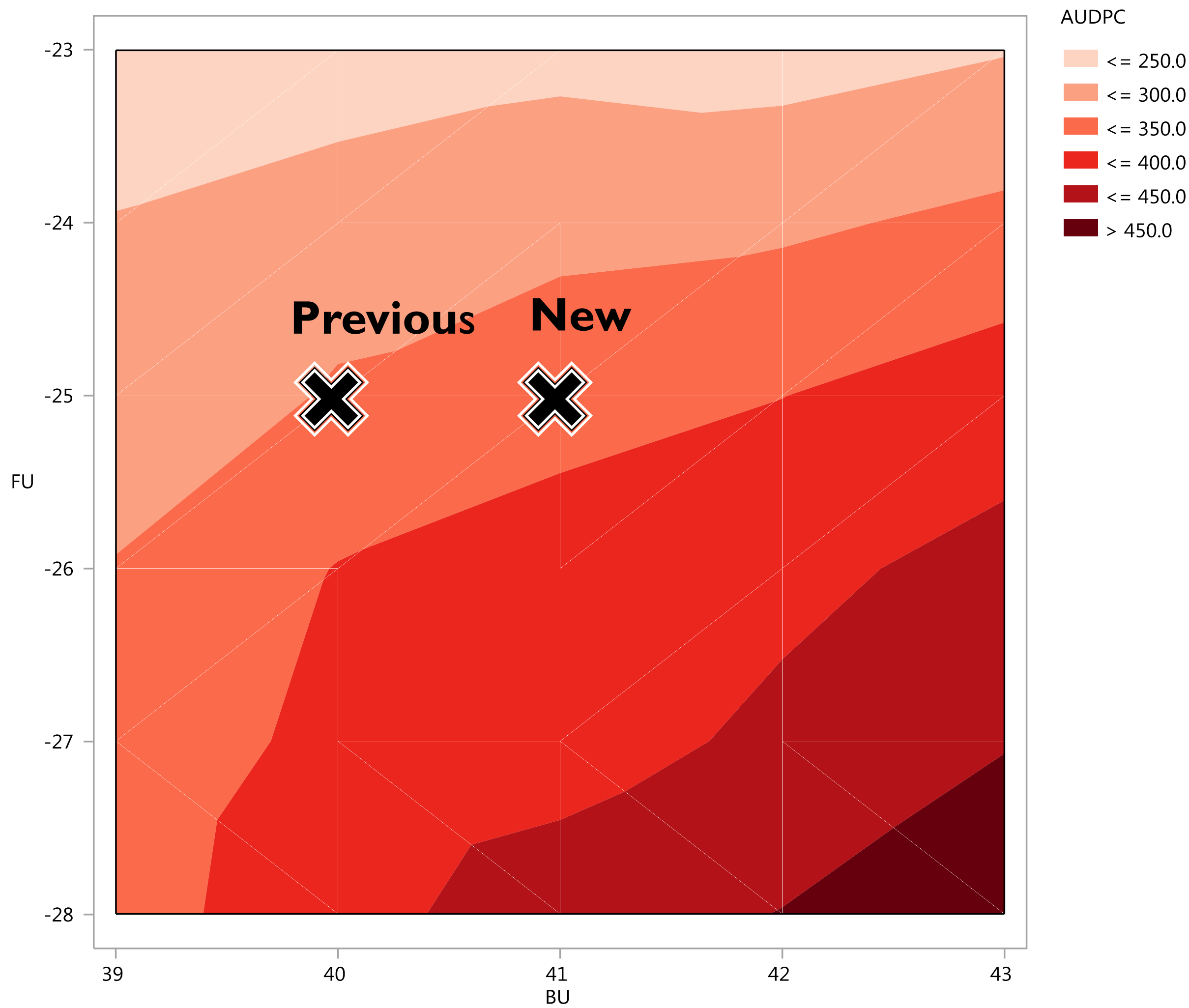

Figure 13. Contour plot of Area Under Disease Progress Curve (AUDPC) for combinations of critical blight unit and fungicide unit thresholds for susceptible cultivars for Massachusetts. The X indicates either the previous combination of critical thresholds or the new combination of critical thresholds.

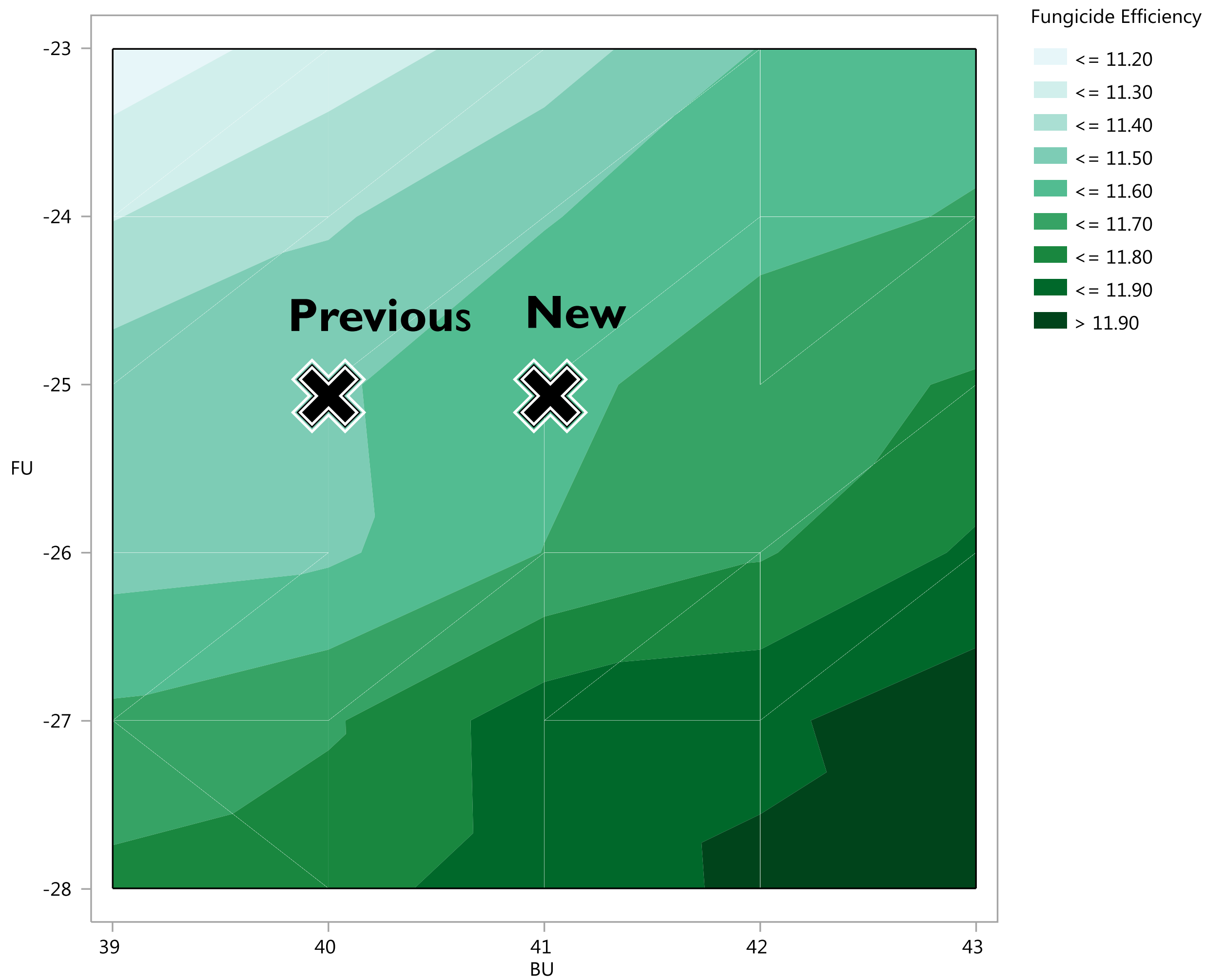

Figure 14. Contour plot of fungicide use efficiency for combinations of critical blight unit and fungicide unit thresholds for susceptible cultivars for Massachusetts. The X indicates either the previous combination of critical thresholds or the new combination of critical thresholds.

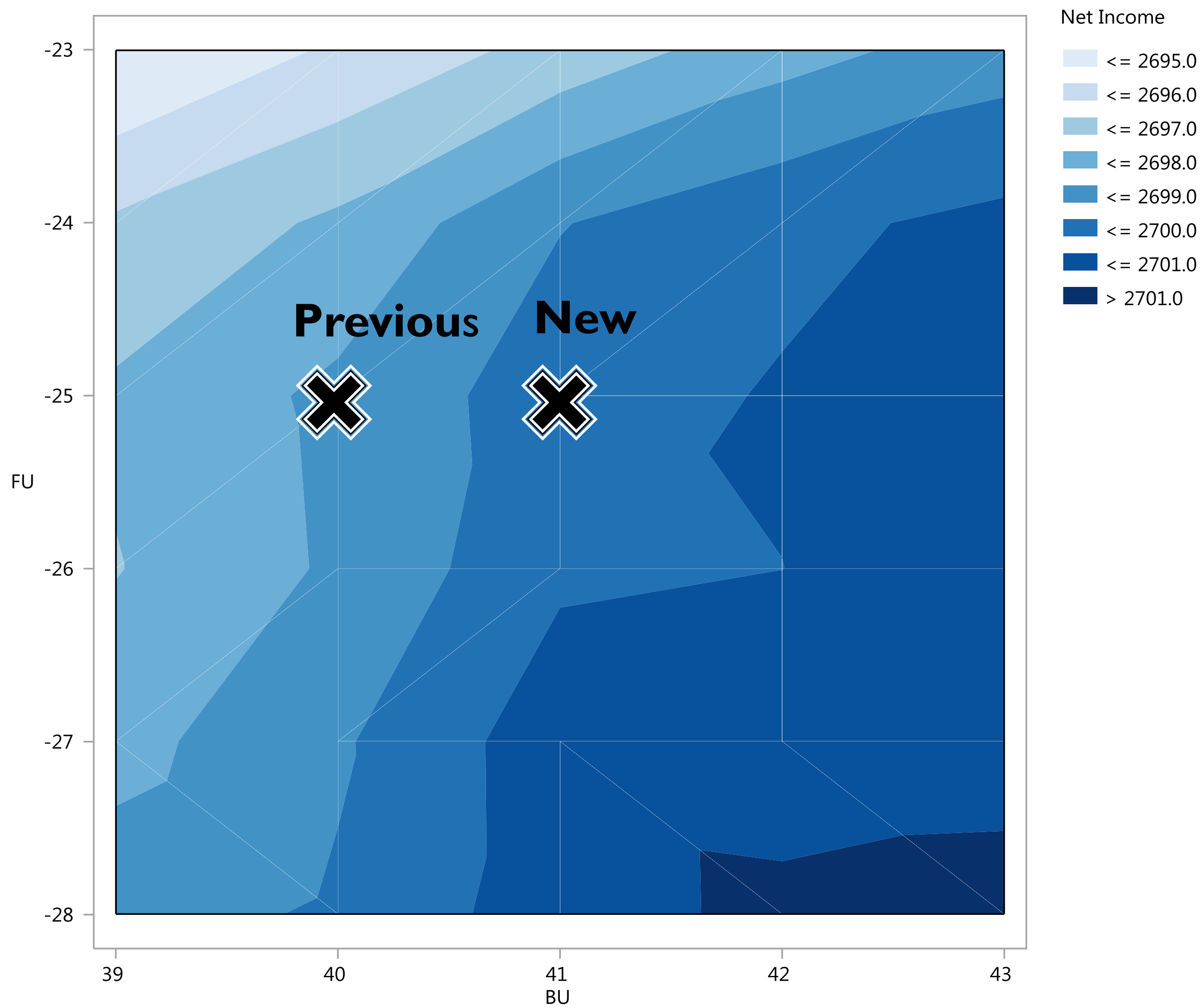

Figure 15. Contour plot of net income for combinations of critical blight unit and fungicide unit thresholds for susceptible cultivars for Massachusetts. The X indicates the combination of critical thresholds or the new combination of critical thresholds.

Table 1. Current Thresholds Used in Simcast System.

Cultivars	**Fungicide**		**Thresholds**	
	Active Ingredients	Product Example	Blight Units	Fungicide Units
Susceptible	chlorothalonil	Bravo WS	30	-15
Moderately Susceptible	chlorothalonil	Bravo WS	35	-20
Moderately Resistant	chlorothalonil	Bravo WS	40	-25

Table 2. Fungicide application cost in 2013.

Name	Quantity	Fungicide Cost	Application Cost	Total fungicide application cost
Bravo WeatherStik	1.5 pints	$8.63 /acre/application	$6.58 /acre/application	$15.21 acre/application

*Fungicide price is obtained from local agricultural chemical distributor on Long Island by Dr. M. T. McGrath in April 2013 (M. T. McGrath, personal communication, December 29, 2013). Application cost ($6.58/acre/application) comes from Lazarus (2013) and includes fuel, lubricants, repairs and maintenance, labor, power, implement depreciation (depreciation is both time-related and use-related), and overhead costs (interest, insurance, and housing). USDA Prices Paid Indices (agricultural chemical and machinery indices) are used to adjust the fungicide price and application cost in 2013 to nominal prices in previous years.

Table 3. Average disease severity (AUDPC) of 152 locations from 2005-2014 for susceptible cultivars.

	Critical Blight Unit															
Critical Fungicide Unit	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
-13	61	79	95	109	129	137	149	160	183	203	222	239	251	268	277	288
-14	113	132	162	191	216	237	260	280	326	362	394	412	428	440	465	482
-15	144	170	224	252	290	339	368	397	449	489	540	576	598	626	667	696
-16	178	222	274	309	371	425	466	508	555	590	648	702	741	778	832	883
-17	205	256	314	358	446	506	549	600	659	706	766	828	884	945	1016	1073
-18	226	280	344	410	510	569	619	677	758	824	904	995	1048	1115	1187	1258
-19	254	308	393	473	575	619	681	760	838	931	1008	1103	1164	1259	1338	1420
-20	262	324	422	498	611	661	727	807	892	985	1076	1192	1264	1370	1448	1531
-21	275	345	437	527	644	688	765	850	933	1031	1144	1272	1361	1449	1530	1621
-22	283	360	446	532	658	693	776	866	955	1069	1182	1320	1411	1499	1579	1654
-23	287	364	450	547	678	711	785	891	985	1101	1228	1365	1468	1548	1626	1713
-24	291	368	460	559	687	726	800	907	998	1124	1261	1401	1510	1582	1656	1743
-25	287	372	463	561	689	731	813	925	1015	1143	1288	1433	1529	1600	1678	1774

represent the Blight Unit and Fungicide Unit thresholds where the lowest average AUDPC was achieved.
represent the Blight Unit and Fungicide Unit thresholds previously in the system.
represent the Blight Unit and Fungicide Unit thresholds where the highest average AUDPC was achieved.

Table 4. Average fungicide use efficiency of 152 locations from 2005-2014 for susceptible cultivars.

	Critical Blight Unit															
Critical Fungicide Unit	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
-13	6.3	6.4	6.5	6.6	6.8	6.8	6.9	7.0	7.0	7.1	7.2	7.2	7.3	7.3	7.3	7.4
-14	6.4	6.5	6.7	6.8	6.9	7.0	7.1	7.2	7.2	7.3	7.3	7.4	7.4	7.5	7.5	7.6
-15	6.5	6.7	6.8	6.9	7.0	7.1	7.1	7.2	7.3	7.4	7.4	7.4	7.5	7.5	7.6	7.6
-16	6.6	6.7	6.9	7.0	7.1	7.1	7.2	7.3	7.4	7.4	7.5	7.5	7.6	7.6	7.6	7.6
-17	6.6	6.8	6.9	7.0	7.1	7.2	7.2	7.3	7.4	7.5	7.5	7.6	7.6	7.6	7.6	7.6
-18	6.7	6.8	7.0	7.1	7.1	7.2	7.3	7.4	7.4	7.5	7.5	7.5	7.5	7.6	7.6	7.6
-19	6.7	6.8	7.0	7.1	7.2	7.3	7.3	7.4	7.4	7.5	7.5	7.5	7.5	7.5	7.5	7.5
-20	6.7	6.9	7.0	7.1	7.2	7.3	7.3	7.4	7.4	7.5	7.5	7.5	7.5	7.5	7.5	7.5
-21	6.8	6.9	7.0	7.1	7.2	7.3	7.3	7.4	7.4	7.5	7.5	7.5	7.4	7.5	7.5	7.4
-22	6.8	6.9	7.0	7.1	7.2	7.3	7.3	7.4	7.5	7.5	7.5	7.5	7.4	7.5	7.5	7.4
-23	6.8	6.9	7.1	7.1	7.2	7.3	7.4	7.4	7.5	7.5	7.5	7.4	7.4	7.4	7.4	7.4
-24	6.8	6.9	7.1	7.1	7.2	7.3	7.4	7.4	7.5	7.5	7.4	7.4	7.4	7.4	7.4	7.4
-25	6.8	6.9	7.1	7.1	7.3	7.4	7.4	7.4	7.5	7.4	7.4	7.4	7.3	7.4	7.4	7.4

represent the Blight Unit and Fungicide Unit thresholds where the highest average fungicide use efficiency was achieved.
represent the Blight Unit and Fungicide Unit thresholds previously in the system.
represent the Blight Unit and Fungicide Unit thresholds where the lowest average fungicide use efficiency was achieved.

Table 5. Average net income ($/Acre) of 152 locations from 2005-2014 for susceptible cultivars.

	Critical Blight Unit															
Critical Fungicide Unit	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
-13	3135	3140	3145	3149	3153	3156	3157	3159	3161	3163	3165	3167	3167	3168	3169	3170
-14	3139	3144	3149	3152	3157	3159	3160	3163	3162	3163	3163	3165	3165	3167	3168	3169
-15	3141	3146	3150	3155	3158	3158	3158	3160	3160	3160	3159	3159	3159	3160	3160	3161
-16	3142	3146	3150	3154	3157	3157	3156	3158	3158	3158	3157	3156	3155	3156	3155	3152
-17	3143	3147	3152	3155	3156	3154	3154	3153	3154	3153	3152	3153	3150	3145	3141	3138
-18	3144	3148	3152	3152	3151	3150	3151	3150	3148	3148	3144	3140	3136	3130	3125	3120
-19	3144	3146	3148	3146	3146	3146	3146	3142	3143	3140	3135	3130	3125	3116	3108	3100
-20	3143	3146	3146	3145	3145	3144	3144	3141	3138	3135	3126	3119	3113	3099	3090	3082
-21	3143	3145	3145	3143	3144	3143	3143	3139	3135	3129	3119	3110	3101	3089	3081	3071
-22	3142	3144	3144	3144	3143	3143	3143	3138	3134	3124	3113	3103	3093	3084	3076	3068
-23	3142	3144	3145	3143	3142	3142	3142	3138	3131	3121	3110	3100	3088	3079	3072	3063
-24	3143	3145	3145	3143	3141	3141	3141	3135	3130	3120	3107	3097	3085	3074	3067	3059
-25	3144	3145	3145	3143	3141	3142	3141	3134	3128	3119	3105	3093	3082	3072	3063	3053

represent the Blight Unit and Fungicide Unit thresholds where the highest average net income was achieved.
represent the Blight Unit and Fungicide Unit thresholds previously in the system.
represent the Blight Unit and Fungicide Unit thresholds where the lowest average net income was achieved.

Table 6. Average disease severity (AUDPC) of 152 locations from 2005-2014 for moderately susceptible cultivars.

	Critical Blight Unit															
Critical Fungicide Unit	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
-15	142	159	169	193	210	226	246	267	293	305	308	322	331	340	353	357
-16	187	212	229	245	282	323	357	388	408	426	445	465	485	503	525	533
-17	236	271	303	334	384	433	486	533	563	577	609	639	674	692	715	726
-18	298	351	390	427	479	536	594	640	685	712	758	800	842	870	899	933
-19	353	412	467	526	571	639	720	774	827	865	917	966	1012	1049	1090	1132
-20	387	460	519	581	648	733	822	890	932	990	1035	1105	1162	1191	1248	1306
-21	419	490	576	646	722	798	888	959	1018	1083	1133	1200	1279	1322	1379	1431
-22	439	508	614	687	756	844	956	1027	1089	1169	1220	1301	1387	1431	1491	1553
-23	472	544	650	726	807	892	1012	1098	1173	1262	1326	1404	1495	1543	1602	1666
-24	503	575	682	743	828	921	1035	1127	1226	1310	1379	1481	1581	1646	1726	1783
-25	527	603	699	757	840	942	1071	1163	1263	1366	1443	1536	1648	1713	1784	1847

represent the Blight Unit and Fungicide Unit thresholds where the lowest average AUDPC was achieved.
represent the Blight Unit and Fungicide Unit thresholds previously in the system.
represent the Blight Unit and Fungicide Unit thresholds where the highest average AUDPC was achieved.

Table 7. Average fungicide use efficiency of 152 locations from 2005-2014 for moderately susceptible cultivars.

Critical Fungicide Unit	Critical Blight Unit 25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
-15	7.7	7.8	7.9	8.0	8.1	8.2	8.2	8.3	8.4	8.4	8.4	8.5	8.6	8.6	8.6	8.6
-16	7.9	8.0	8.1	8.2	8.3	8.3	8.4	8.5	8.5	8.6	8.6	8.7	8.7	8.7	8.8	8.8
-17	8.0	8.1	8.2	8.3	8.4	8.5	8.5	8.6	8.6	8.7	8.7	8.8	8.8	8.8	8.8	8.9
-18	8.2	8.2	8.3	8.4	8.5	8.6	8.6	8.7	8.7	8.8	8.8	8.8	8.8	8.9	8.9	8.9
-19	8.2	8.3	8.4	8.5	8.6	8.6	8.7	8.7	8.7	8.8	8.8	8.8	8.8	8.9	8.8	8.8
-20	8.3	8.4	8.5	8.6	8.6	8.7	8.7	8.7	8.8	8.8	8.8	8.8	8.8	8.9	8.8	8.8
-21	8.4	8.4	8.5	8.6	8.6	8.7	8.7	8.7	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8
-22	8.4	8.5	8.5	8.6	8.7	8.7	8.7	8.7	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.7
-23	8.4	8.5	8.5	8.6	8.6	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
-24	8.4	8.5	8.5	8.6	8.6	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.6	8.6	8.6	8.6
-25	8.4	8.5	8.5	8.6	8.7	8.7	8.8	8.8	8.8	8.7	8.7	8.7	8.6	8.6	8.6	8.6

represent the Blight Unit and Fungicide Unit thresholds where the highest average fungicide use efficiency was achieved.
represent the Blight Unit and Fungicide Unit thresholds previously in the system.
represent the Blight Unit and Fungicide Unit thresholds where the lowest average fungicide use efficiency was achieved.

Table 8. Average net income ($/Acre) of 152 locations from 2005-2014 for moderately susceptible cultivars.

		Critical Blight Unit															
		25	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
Critical Fungicide Unit	**-15**	3180	3182	3185	3186	3188	3190	3192	3193	3194	3195	3196	3197	3198	3199	3199	3199
	-16	3184	3185	3188	3190	3191	3192	3193	3194	3195	3195	3195	3196	3197	3198	3198	3198
	-17	3185	3186	3189	3190	3190	3191	3191	3190	3190	3191	3191	3191	3190	3191	3191	3190
	-18	3185	3184	3186	3187	3187	3188	3188	3188	3185	3185	3184	3183	3183	3184	3183	3181
	-19	3185	3184	3185	3185	3184	3184	3182	3181	3179	3178	3175	3175	3175	3173	3172	3170
	-20	3185	3183	3184	3182	3180	3178	3175	3172	3171	3168	3166	3163	3161	3161	3157	3153
	-21	3184	3183	3182	3180	3177	3174	3172	3169	3167	3163	3159	3156	3153	3151	3146	3142
	-22	3183	3182	3179	3178	3176	3171	3166	3162	3159	3153	3151	3146	3142	3139	3136	3129
	-23	3183	3181	3178	3177	3174	3172	3166	3160	3154	3146	3142	3136	3130	3125	3120	3114
	-24	3181	3179	3176	3177	3174	3170	3164	3157	3150	3142	3137	3128	3119	3110	3103	3100
	-25	3180	3178	3175	3177	3175	3170	3161	3153	3146	3138	3131	3122	3111	3102	3097	3090

represent the Blight Unit and Fungicide Unit thresholds where the highest average net income was achieved.
represent the Blight Unit and Fungicide Unit thresholds previously in the system.
represent the Blight Unit and Fungicide Unit thresholds where the lowest average net income was achieved.

Table 9. Average disease severity (AUDPC) of 152 locations from 2005-2014 for moderately resistant cultivars.

		Critical Blight Unit				
		39	**40**	**41**	**42**	**43**
Critical Fungicide Unit	**-23**	114	121	133	139	150
	-24	148	156	167	177	189
	-25	164	178	197	208	224
	-26	185	204	225	243	261
	-27	206	226	248	267	290
	-28	216	242	273	298	323

represent the Blight Unit and Fungicide Unit thresholds where the lowest average AUDPC was achieved.
represent the Blight Unit and Fungicide Unit thresholds previously in the system.
represent the Blight Unit and Fungicide Unit thresholds where the highest average AUDPC was achieved.

Table 10. Average fungicide use efficiency of 152 locations from 2005-2014 for moderately resistant cultivars.

		Critical Blight Unit				
		39	**40**	**41**	**42**	**43**
Critical Fungicide Unit	**-23**	12.6	12.8	12.8	12.9	13.0
	-24	12.8	12.9	13.0	13.1	13.2
	-25	13.1	13.2	13.2	13.3	13.4
	-26	13.2	13.3	13.4	13.5	13.6
	-27	13.4	13.5	13.6	13.7	13.8
	-28	13.5	13.7	13.7	13.8	13.8

represent the Blight Unit and Fungicide Unit thresholds where the highest average fungicide use efficiency was achieved.
represent the Blight Unit and Fungicide Unit thresholds previously in the system.
represent the Blight Unit and Fungicide Unit thresholds where the lowest average fungicide use efficiency was achieved.

Table 11. Average net income ($/Acre) of 152 locations from 2005-2014 for moderately resistant cultivars.

		Critical Blight Unit				
		39	**40**	**41**	**42**	**43**
Critical Fungicide Unit	**-23**	3259	3260	3261	3262	3263
	-24	3261	3262	3264	3264	3265
	-25	3263	3264	3265	3266	3267
	-26	3264	3266	3266	3267	3268
	-27	3266	3266	3267	3268	3269
	-28	3267	3267	3268	3269	3269

(green) represent the Blight Unit and Fungicide Unit thresholds where the highest average net income was achieved.
(blue) represent the Blight Unit and Fungicide Unit thresholds previously in the system.
(red) represent the Blight Unit and Fungicide Unit thresholds where the lowest average net income was achieved.

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