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Efficacy of Conventional Fungicides for Downy Mildew in Field-Grown Sweet Basil in the United States

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Abstract

Application of fungicides has been the main management practice for *Peronospora belbahrii*, which is the most important pathogen of sweet basil in the United States. Six replicated experiments were conducted between 2010 and 2016 with field-grown basil of a susceptible cultivar exposed to naturally occurring wind-dispersed sporangiospores of *P. belbahrii* to evaluate conventional fungicides registered for basil downy mildew in the United States and in development for this use. This project revealed the importance for successful management of using a preventive fungicide application schedule, maintaining a 7-day application interval, and using application equipment designed to provide thorough spray coverage to plants (drop nozzles). Fungicide efficacy was assessed based on incidence of symptomatic leaves rather than disease severity, which is stringent but realistic because there is zero tolerance for disease on fresh-market herbs. Most fungicides were tested as the formulated product marketed in the United States. Oxathiapiprolin was tested as experimental formulations. Its trade name is Orondis. Overall best control was achieved in 2016. Excellent control (99% based on AUDPC values) was obtained with four fungicide programs with oxathiapiprolin, Revus, and ProPhyt, indicating this combination of chemistry was more important than specific timing for each fungicide. Ranman applied in alternation with Revus plus K-Phite was not quite as effective (89% control); this treatment was ineffective in 2015 when the 7-day spray interval was not maintained. Best treatment in 2015 was Quadris applied in alternation with Revus plus oxathiapiprolin for two of three Revus applications. Two different alternations of these fungicides also were effective. But Quadris alternated with Revus was ineffective. When tested singly, the most effective fungicides in 2013 (listed in order based on AUDPC values) were Zampro, Revus, oxathiapiprolin, and Ranman. ProPhyt was effective in 2013 but not in 2012, when another phosphorous acid fungicide, K-Phite, also was ineffective. Only oxathiapiprolin and Zampro were effective in the 2012 experiment; Revus and Ranman were ineffective. Presidio was ineffective both years. Based on the results from this study, Orondis is the most effective fungicide among those evaluated for managing basil downy mildew, and Zampro is second. Neither were labeled for this use on field-grown basil as of June 2020. Ranman applied in alternation with Revus plus K-Phite, a commonly recommended program of labeled fungicides, provided very good control.

Keywords: *Peronospora belbahrii*, *Ocimum basilicum*, chemical control

Downy mildew quickly became the most important disease of sweet basil (*Ocimum basilicum* L.) in the United States following its first detection in 2007 (Roberts et al. 2009). Prior to this, the pathogen was widely reported in Europe (Wyenandt et al. 2015). The pathogen, *Peronospora belbahrii* Thines, produces an abundance of wind-dispersed sporangiospores and can be seed-borne (Garibaldi et al. 2004), which has enabled downy mildew to occur widely every year in the United States (Roberts et al. 2009). It has been detected in 42 states, including Hawaii, plus the District of Columbia (Wyenandt et al. 2015). Significant economic losses have occurred in field and greenhouse production (Wyenandt et al. 2015).

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Managing downy mildew has been an essential component of producing sweet basil in the United States. The disease affects leaves, the consumed part of the plant. Market demand requires disease-free tissue for fresh-market consumption. Pathogens such as *P. belbahrii* that produce spores easily dispersed by wind can be difficult to avoid, especially with outdoor crops. This has proven to be the case for basil downy mildew. With high humidity and dew providing favorable conditions for infection (Cohen et al. 2017; Wyenandt et al. 2015), manipulating the environment such as by using drip rather than overhead irrigation to minimize leaf wetness is not a viable option for managing this disease. All cultivars of sweet basil tested were found to be susceptible (Wyenandt et al. 2010). Spice types of basil are less susceptible but are not a suitable replacement for sweet basil, and they fill different market demands. Developing resistant cultivars through traditional breeding typically takes years to accomplish and has been ongoing for sweet basil since downy mildew was recognized as a major constraint to basil production (Ben-Naim et al. 2018; Pyne et al. 2015). However, in recent years, resistant cultivars have been commercially available (e.g., Amazel, Rutgers Devotion DMR, and Prospera). Resistance typically is not complete (immunity), and an integrated approach to management with fungicides is recommended to minimize selection of a new pathogen race able to overcome resistance. Thus, the main management practice for this disease in the United States since 2007 has been the timely application of fungicides.

The number of conventional (nonorganic) fungicide chemistries available for growers to use in the United States on field-grown basil has increased from three when basil downy mildew first appeared to six in 2019, with another expected to be labeled soon. Mefenoxam (Fungicide Resistance Action Committee [FRAC] code 4) formulated as Ridomil Gold SL (Syngenta Crop Protection, Greensboro, NC) and azoxystrobin (FRAC code 11) formulated as Quadris (Syngenta Crop Protection) were labeled for use on basil but not specifically for downy mildew in 2007. They could be used in states not

requiring the target pest to be specified on the label. There were two phosphorous acid (phosphanate) fungicides (FRAC code P 07) labeled for this disease in 2007; several more have been labeled since. Products include Fosphite (JH Biotech, Ventura, CA), Fungi-Phite (Plant Protectants, Visalia, CA), K-Phite (Plant Food Systems, Zellwood, FL), pHorsepHite (Loveland Products, Loveland, CO), ProPhyt (Helena Chemical Company, Collierville, TN), and Rampart (Loveland Products). Cyazofamid (FRAC code 21) formulated as Ranman (FMC Agricultural Products, Philadelphia, PA) was labeled for basil downy mildew in 2012. Mandipropamid (FRAC code 40) formulated as Revus (Syngenta Crop Protection) was labeled for this use in 2014. Fenamidone (FRAC code 11) formulated as Reason 500 SC (Bayer CropScience, St. Louis, MO) was labeled for this use in 2017. Fluopicolide (FRAC code 43) formulated as Presidio (Valent U.S.A., Walnut Creek, CA) was labeled for this use in 2019. Ranman, Revus, Reason, and Presidio were registered as a result of work conducted by the IR-4 project in collaboration with university researchers. Oxathiapiprolin (FRAC code 49) formulated as Orondis Ultra (Syngenta Crop Protection) is anticipated to be labeled for this use in the near future. Oxathiapiprolin formulated as Segovis for ornamental crops is labeled for use on basil grown in greenhouses. Targeted oomycete fungicides such as those listed above have greater potential to provide effective suppression of basil downy mildew than contact fungicides due to their modes of action and their ability to translocate to the abaxial surface of leaves. The abaxial surface is considered more favorable for infection than the adaxial surface due to higher density of stomata, although *P. belbahrii* can also infect by direct penetration (Cohen et al. 2017), higher humidity, and lower exposure to UV radiation.

The objective of this study was to evaluate conventional fungicides currently registered and those in commercial development for basil downy mildew in the United States. Both individual fungicides and combination programs were examined during the course of these trials in New York. Experiments were conducted with field-grown basil exposed to naturally occurring wind-dispersed sporangiospores of *P. belbahrii*.

Materials and Methods

Replicated experiments were conducted in 2010, 2011, 2012, 2013, 2015, and 2016 under field conditions at the Cornell University research facility on Long Island, NY. Plots were single beds with one or two staggered rows of basil at 9-inch plant spacing. Beds had drip irrigation and were covered with black plastic mulch after spreading and incorporating fertilizer (10-10-10). Practices used to manage weeds between beds varied among experiments and included applying herbicide, cultivating, mowing, and/or hand weeding. Basil was seeded during June (2012 to 2016) or July (2010 and 2011) in trays in a greenhouse, placed outdoors to harden for about a week, and then transplanted by hand during mid-July (2012 to 2016) into single-row plots or mid-August (2010 and 2011) into beds with two staggered rows. The basil downy mildew susceptible cultivar 'Italian Large Leaf' (Johnny's Selected Seeds) was used in 2010 to 2013, and 'Genovese' (Stokes Seeds) was used in 2015 and 2016.

Foliar fungicides (Table 1) were applied with a backpack sprayer beginning before or after symptoms were found in the field, which included a row of basil planted before the plots were planted to serve as a spreader row that was not treated with fungicides. A boom with a single (TJ60-4004EVS) nozzle delivering spray to the top of plants was used in 2010 and 2011. Starting in 2012, this boom was used for the first applications until basil plants were large enough to use a boom with two drop nozzles directed to the side of plants as well as a nozzle delivering spray over the top of the plant. This boom was used to improve coverage achieved with a single nozzle directed to the top of plants. Fungicide treatments were applied on a weekly (7-day) schedule except when weather delayed applications. Two fungicide treatments in 2013 started with a soil drench application made around the plant stem 2 days after transplanting.

Table 1. Foliar, conventional fungicides evaluated for basil downy mildew

Trade name	Active ingredient	FRAC code
K-Phite, ProPhyt	Phosphorous acid	P 07
Orondis	Oxathiapiprolin[z]	49
Presidio	Fluopicolide	43
Previcur Flex	Propamocarb hydrochloride	28
Quadris	Azoxystrobin	11
Ranman	Cyazofamid	21
Revus	Mandipropamid	40
Ridomil Gold SL	Mefenoxam	4
Zampro	Ametoctradin	45

[z] Oxathiapiprolin was tested as QGU42 in 2012, Zorvec in 2013, A20941A in 2015, A21591C (premix with mandipropamid now marketed as Orondis Ultra) in 2016, and A21723E (premix with mefenoxam; discontinued formulation of Orondis Gold) in 2016.

Naturally occurring inoculum was relied on. Long-distance wind-dispersed sporangiospores from infected plants are considered to be the primary source of initial inoculum in the region. Basil was planted late in the growing season, because downy mildew is more prevalent during late summer on Long Island, and thus a midsummer transplant time would increase the likelihood of disease development during the experiments.

Downy mildew was rated weekly in each plot as percent affected leaves with sporulation of the pathogen visible on the underside. Incidence was assessed rather than severity, because any amount of symptoms renders a leaf unmarketable. The number of plants affected and percentage of leaves affected on up to 10 affected plants was determined at each assessment. Area under the disease progress curve (AUDPC) values were calculated from first to last assessment using the following formula: $\sum n_{i=1}[(R_{i+1} + R_i)/2]\ (t_{i+1} - t_i)$, where R is the disease incidence rating (% leaves with symptoms on affected plants) at the i^{th} observation, t_i is the time (days) since the previous rating at the i^{th} observation, and n is the total number of observations. In 2010 a destructive sampling was done at the end of the season on 13 October so that plants could be held upside down to obtain a more thorough view of the underside of leaves.

A randomized complete block design with four replications was used for all experiments. Statistical analysis was performed using the software program SAS-JMP (SAS Institute, Cary, NC). Graphs of residuals were examined for a pattern indicating the need to transform data before analysis. Mean separation was conducted using Tukey's HSD ($P = 0.05$).

Additional information about methods used, including fertilizer, practices used to manage weeds, and environmental conditions, were published in preliminary reports about each experiment (McGrath 2016; McGrath and Hunsberger 2011, 2012; McGrath and LaMarsh 2013, 2014; McGrath and Sexton 2017). Most experiments also included treatments suitable for organic production, which are not reported here.

Results

Downy mildew became severe on the nontreated control plants in all experiments except in 2010; thus, there usually was high disease pressure for evaluating fungicides in the experiments.

2010. Symptoms of downy mildew were first observed on 16 August on one leaf in a spreader row. Symptoms were not found in treatment plots until 20 September, which was after the fourth application. Fungicides were applied weekly for 7 weeks. Rates were applied lower than intended on the first three dates (24 August to 6 September) due to a calculation error; these were before symptoms were found in any plots and thus likely had little if any impact on results. No symptoms were found in any of the four replicate plots treated with ProPhyt (phosphorous acid, FRAC code P 07) at the first assessment (Table 2). However, neither ProPhyt nor Revus (mandipropamid, FRAC code 40) were effective in controlling basil downy mildew during the course of the trial.

2011. Symptoms of downy mildew were first observed in the spreader row on 19 August and in the plots on 25 August. Fungicides were applied weekly for 6 weeks starting on 11 August. A hurricane plus rain occurring on many additional days in late August and September provided atypical environmental conditions for the region during the experiment. Conditions were extremely favorable for disease development but not for applying fungicide treatments or for plant growth. The strong winds and intensive rainfall occurring

during the storms, especially during Hurricane Irene on 28 August, damaged research plants. Rain fell on 10 days during August, delivering a total of 10.6 inches. Another major rainfall of 3.4 inches occurred over 6 to 8 September. Although there were numerically fewer leaves with downy mildew symptoms on plants treated with ProPhyt or Revus compared with nontreated control plants, none of the assessments were significantly different (Table 3).

2012. Symptoms of downy mildew were first observed in plots on 16 August. Fungicides were applied weekly for 8 weeks starting on 7 August. Downy mildew was effectively suppressed only by oxathiapiprolin and only based on incidence of affected leaves on 7 September and on AUDPC value (Table 4). Zampro was effective based on the assessment on 7 September. Incidence of leaves with downy mildew symptoms often was lower, albeit not significantly, on plants treated with the other fungicides compared with the nontreated control plants, with the exception of Previcur Flex. There were no significant differences among treatments at the final assessment 2 weeks following the last application. The two phosphorous acid fungicides, K-Phite and ProPhyt, were not significantly different.

2013. Symptoms of downy mildew were first observed on 6 August, which was at least 10 days earlier than previous experiments. Foliar fungicide applications were started the next day. The most effective fungicide treatments consisted of a soil drench of ProPhyt or Regalia followed by foliar applications of oxathiapiprolin (Table 5). However, these treatments were not significantly better than oxathiapiprolin used alone or than foliar treatments with Zampro, Revus, or Ranman. Ranman applied in alternation with Fracture (FRAC M12) was effective only at the first assessment. ProPhyt was effective based on the last two assessments, whereas Presidio was ineffective. The fungicides tested might have been more effective if applied as intended on a preventive schedule.

2015. Symptoms of downy mildew were first observed in the spreader row on 10 August. Following two days with rain, 11 and 21 August, symptoms were found on almost all plants in plots on 27 August, 2 days after the fourth application. Most treatments were ineffective (Table 6), which may at least partly reflect the fact that applications were not made weekly as intended. The actual intervals between the six applications were 10, 5, 13, 7, and 7 days, respectively. Likely the most critical lapse in the spray schedule impacting control occurred with the fourth application, which was to be made on 19 August, 2 days before it rained, but was instead made 4 days after rain and 13 days after the previous application. This documents the importance of maintaining a regular application schedule to manage basil downy mildew. The most effective treatment on 24 August was the program in which oxathiapiprolin was applied on 12 August, which was the application immediately preceding rain. The most effective treatments based on incidence, AUDPC, and defoliation are the combination programs of oxathiapiprolin applied with Revus, suggesting that oxathiapiprolin (alone or the combination) is more effective than the other fungicides in the three similar programs that were compared. These three programs were the only treatments with significantly less defoliation than the control on 31 August. Assessments on 17 and 28 September were 9 and 20 days after the last application and thus provide measures of residual activity.

2016. Symptoms of downy mildew were first observed on 15 August in six of the 28 plots. On 22 August, symptoms were observed in all nontreated plots on an average of 80% of plants, but very few leaves had symptoms. Foliar fungicide applications were started 1 day after transplanting and 3 weeks before symptoms were seen. All three treatments containing a rotation of Orondis Ultra, Revus, and ProPhyt at various timings were equally highly effective in controlling downy mildew and exhibited good residual activity, providing more than 99% control compared with the nontreated plots 2 weeks after the final application (Table 7). The treatment containing a rotation of Revus and ProPhyt was similarly effective at controlling downy mildew, providing 99% control compared with the nontreated plots. These four highly effective fungicide programs started with a soil drench treatment of Ridomil Gold or A21723E (oxathiapiprolin + mefenoxam) at transplanting, which was 21 days before symptoms were first seen. The treatment containing a rotation of Ranman, Revus, and K-Phite was less effective at controlling downy mildew compared with the most effective treatments but still provided significant control when compared with the nontreated plots: 89% control 1 week after the final application. The treatment containing successive applications of an experimental fungicide, F9177-1, was much less effective than any other fungicide treatment but still provided significant control when compared with the nontreated plots: 43% control 1 week after the final application. The four best treatments also continued to provide stellar control of downy mildew (>99% compared with nontreated plots) 2 weeks after the final fungicide application, whereas other treatments began to decline in their effectiveness.

Discussion

The results of this project indicate the importance for successful control of basil downy mildew of using a preventive application schedule, maintaining a 7-day application interval, and using application equipment designed to provide thorough spray coverage to plants. Revus was ineffective in the 2010 and 2011 experiments when applied with a single-nozzle boom directing the spray to the top leaves of plants, even though fungicide applications were started before symptoms were found, whereas Revus was effective in 2013 when applied using a boom that also had two drop nozzles delivering fungicide spray to the side of plants.

Table 3. Efficacy of fungicides for managing downy mildew in basil in 2011

	Downy mildew incidence (% leaves with symptoms)[y]			
Treatment (rate/ha)[x]	25 Aug	1 Sep	9 Sep	AUDPC[z]
Nontreated control	6.2	14.7	41.0	307.4 ab
ProPhyt 4,675 ml	2.2	4.3	25.5	148.7 b
Revus 584 ml	3.7	3.4	25.3	142.3 b
Treatment *P* value	0.8678	0.0357	0.1085	0.0063

[x] Rate of formulated product/ha. All treatments were applied on 11 Aug, 17 Aug, 24 Aug, 31 Aug, 7 Sep, and 14 Sep. Treatments listed after the control in order based on area under the disease progress curve (AUDPC) values.
[y] Means followed by the same letter or no letter are not statistically different from each other (Tukey's HSD, $P = 0.05$).
[z] AUDPC values were square-root transformed before analysis.

Table 2. Efficacy of fungicides for managing downy mildew in basil in 2010

	Plants affected by downy mildew (%)				Postharvest	
Treatment (rate/ha)[x]	24 Sep	6 Oct	13 Oct	AUDPC[y]	Plants affected (%)	Incidence (%)
Nontreated control	12.7 abc[z]	34.4 ab	50.0	50.6 ab	53.61	2.83
ProPhyt 4,675 ml	0.0 c	22.3 b	58.2	44.5 b	36.11	4.35
Revus 584 ml	5.3 bc	20.3 b	56.6	43.0 b	33.33	7.32
Treatment *P* value	0.0003	0.0010	0.3934	0.0173	0.0947	0.4519

[x] Rate of formulated product/ha. Application dates were 24 Aug, 1 Sep, 6 Sep, 14 Sep, 22 Sep, 28 Sep, and 7 Oct. Treatments listed after the control in order based on area under the disease progress curve (AUDPC) values.
[y] AUDPC calculated from plant severity data.
[z] Means in a column followed by the same letter or no letter are not statistically different from each other (Tukey's HSD, $P = 0.05$).

Limited efficacy detected in these experiments is at least partly due to the stringent, albeit realistic, assessment used. Percent leaves affected (incidence) was assessed rather than severity of disease on the leaves because there is zero tolerance for disease on fresh market herbs. Other researchers have used severity on leaves or whole plant ratings to assess fungicide efficacy.

Oxathiapiprolin (FRAC code 49) was effective when tested singly, and fungicide programs that included oxathiapiprolin were also effective. Several formulations were used in the current study (Table 1). It also was effective when tested in Florida as QGU42 (Raid et al. 2013) and in Illinois as A21591C (Babadoost and Sulley 2018). Oxathiapiprolin is in three fungicides now registered in the United States for use on vegetable crops under the trade name Orondis. None were labeled for use on basil as of March 2020. Tolerances established for residues are 10 ppm for fresh basil leaves and 80 ppm for dried leaves. Mode of action is to bind to the oxysterol-binding protein in oomycetes (https://www.frac.info/).

Presidio (fluopicolide, FRAC code 43) was ineffective both years that it was tested (2012 and 2013). It was effective, exhibiting similar suppression as Ranman, when tested in Florida in two evaluations in 2010 (spring and fall), but Revus was more effective (Raid and Sui 2011b; Raid et al. 2011a), as was Zampro when tested (Raid and Sui 2011b). Quadris was more effective in one evaluation and similar in the other. Presidio was not as effective as Revus, Forum, Ranman, ProPhyt, or Zampro when compared in Illinois (Babadoost and DeYoung 2012). Presidio is registered for managing downy mildew in basil in the United States. Tolerances for residues are 40 ppm for fresh leaves and 200 ppm for dried leaves. One day is the minimum time from last application until harvest (preharvest interval). Mode of action is delocalization of spectrin-like proteins, which are cytoskeleton and motor proteins (https://www.frac.info/).

ProPhyt (phosphorous acid, FRAC code P 07) was effective in some experiments. K-Phite, another fungicide with a related active ingredient, was ineffective the only time it was tested alone. They were components of fungicide programs that were effective. In sharp contrast, K-Phite applied alone on a weekly, preventive schedule was very effective in two experiments in New Jersey and outperformed Revus, Ranman, Presidio, Reason, and azoxystrobin formulated as Amistar (Homa et al. 2014). ProPhyt was effective in Illinois (Babadoost and DeYoung 2012). ProPhyt, K-Phite, and Rampart were effective in New Jersey (Wyenandt and Simon 2014). ProPhyt and K-Phite exhibited good efficacy when tested in Florida in 2007, but Forum, Revus, Ranman, Reason, and Ridomil Gold were more effective (Raid 2008e). In another experiment, ProPhyt was more effective than Previcur Flex and less effective than Revus (Raid 2008a). In a subsequent experiment, ProPhyt was only moderately effective, with all other fungicides tested performing substantially better (Raid et al. 2013). ProPhyt applied with Revus, Reason, or Ranman provided good control, better than ProPhyt alone (Raid 2008h). Rampart applied with Amistar, Forum, Presidio, Previcur Flex, Reason, Revus, or Ranman provided control better than any of these eight fungicides applied alone (Raid 2008d, 2008g). Quadris

Table 4. Efficacy of fungicides for managing downy mildew in basil in 2012

	Downy mildew incidence (% leaves with symptoms)[x]					
Treatment (rate/ha)[w]	**24 Aug**	**31 Aug**	**7 Sep**	**14 Sep**	**AUDPC[y]**	**11 Oct**
Nontreated control	6.2 ab	20.3	54.7 ab	26.2	650.7 a	54.0
K-Phite 7,013 ml	0.9 b	19.2	34.9 abcd	14.5	442.4 ab	46.5
ProPhyt 7,013 ml	2.1 b	11.0	41.0 abcd	9.3	410.6 ab	33.8
Previcur Flex 1,403 ml	11.1 a	17.4	60.1 a	17.9	658.2 a	30.3
Ranman[z] 201 ml	6.4 ab	23.5	37.3 abcd	15.3	516.5 ab	32.5
Presidio 292 ml	2.5 b	17.8	31.6 abcd	10.7	402.0 ab	48.0
Revus[z] 584 ml	0.2 b	10.6	22.0 bcd	4.2	248.5 ab	30.5
Zampro[z] 1,022 ml	1.2 b	14.0	16.0 cd	6.3	243.9 ab	25.5
QGU42 (oxathiapiprolin)[z] 175 ml	0.1 b	8.7	11.9 d	2.6	157.8 b	22.4
Treatment *P* value	0.0026	0.7124	0.0001	0.1413	0.0038	0.0596

[w] Rate of formulated product. Foliar application dates were 7 Aug, 14 Aug, 20 Aug, 27 Aug, 7 Sep, 13 Sep, 20 Sep, and 27 Sep.
[x] Numbers in each column followed by the same or no letter are not significantly different from each other (Tukey's HSD, $P = 0.05$).
[y] Area under the disease progress curve (AUDPC) values were square root transformed before analysis. Table contains de-transformed values.
[z] Ranman and Revus were applied with Silwet L-77 at 0.125% v/v; Zampro and QGU42 were applied with Induce at 0.25% v/v.

Table 5. Efficacy of fungicides for managing downy mildew in basil in 2013

	Downy mildew incidence (% leaves with symptoms)[x]					
Treatment and rate/ha (application dates)[w]	**23 Aug**	**4 Sep**	**11 Sep**	**18 Sep**	**25 Sep**	**AUDPC[y]**
Nontreated	45.3 a	45.5 a	42.5 ab	45.3 a	60.0 a	1,533.1 a
ProPhyt 4,675 ml (1–6)	16.3 ab	32.8 abc	25.5 ab	8.3 bcde	9.5 bc	657.2 bcd
Presidio 292 ml (1–6)	25.3 ab	38.5 ab	39.5 ab	34.0 ab	31.5 abc	1,043.5 ab
Ranman[z] 201 ml (1–6)	8.8 b	8.8 bc	26.5 ab	12.8 bcde	16.3 bc	425.1 cde
Ranman[z] 201 ml (1,3,5), Fracture 2,190 ml (2,4,6)	7.3 b	16.3 abc	55.5 a	32.8 abc	31.3 abc	891.2 abc
Revus[z] 584 ml (1–6)	4.5 b	4.8 bc	13.3 ab	7.5 bcde	13.0 bc	286.5 de
Zampro[z] 1,022 ml (1–6)	6.0 b	9.3 abc	13.0 ab	5.8 cde	7.3 c	251.7 de
Zorvec (oxathiapiprolin)[z] 175 ml (1–6)	7.5 b	12.5 abc	12.5 b	4.3 de	12.8 bc	364.1 cde
ProPhyt 4,675 ml (soil), Zorvec[z] 175 ml (1–6)	13.8 ab	1.5 c	2.5 b	7.5 bcde	12.5 bc	152.9 e
Regalia 7,013 ml (soil), Zorvec[z] 175 ml (1–6)	11.8 b	0.3 c	14.5 ab	0.5 e	2.5 c	138.0 e
Treatment *P* value	0.0011	0.0007	0.0034	<0.0001	<0.0001	<0.0001

[w] Rate of formulated product/ha. Soil drench applications of 1.7 fl oz/plant were made on 17 Jul. Foliar application dates were as follows: 1 = 7 Aug; 2 = 14 Aug; 3 = 21 Aug; 4 = 28 Aug; 5 = 5 Sep; and 6 = 13 Sep.
[x] Numbers in each column with a letter in common are not significantly different from each other (Tukey's HSD, $P = 0.05$).
[y] Area under the disease progress curve (AUDPC) values were square-root transformed before analysis. Table contains de-transformed values.
[z] Ranman and Revus were applied with Silwet L-77 0.125% v/v; Zampro and Zorvec were applied with Induce 0.25% v/v.

applied with Nutri-Phite provided control better than either alone (Raid et al. 2011b). In an evaluation of fungicides in this chemical group, potassium phosphites (ProPhyt, Nutri-Phite, Phostrol, K-Phite, and Agri-Fos) were more effective than calcium phosphite (Calci-Phite), RTRx Plus, Rampart, and Rescue (Raid 2008i). ProPhyt, K-Phite, Fosphite, Fungi-Phite, pHorsepHite, Rampart, and some other phosphorous acid fungicides are registered for managing downy mildew in basil in the United States. Based on all of these results, the use pattern generally recommended for phosphorous acid fungicides is to apply them combined with another targeted fungicide rather than apply them alone, especially after downy mildew has been detected in a crop. Phosphorous acid fungicides are exempt from the requirement of an established tolerance for residues. Mode of action is inhibition of oxidative phosphorylation in the metabolism of oomycetes plus the indirect effect of inducing systemic acquired resistance in plants (https://www.frac.info/).

Quadris (azoxystrobin, FRAC code 11) was only tested as a component of fungicide programs. Those with Orondis and Revus were effective. Azoxystrobin formulated as Amistar, and Reason, another quinone outside inhibitor (QoI) fungicide, were effective when tested in Florida in 2007 (Raid 2008b, 2008c, 2008d, 2008e, 2008f). This chemistry was among the most effective (Raid 2008f). Reason tank mixed with ProPhyt was also effective (Raid 2008h). Quadris plus ProPhyt was not as effective applied on a 14-day interval as on a 7-day interval (Mersha et al. 2012). Only Quadris is registered for managing downy mildew in basil in the United States. Tolerances for residues are 50 ppm for fresh leaves and 260 ppm for dried leaves. Mode of action of QoI fungicides is interference with energy production in fungal cells by blocking electron transfer at the site of quinol oxidation (the Qo site) in the cytochrome bc1 complex, thereby preventing ATP formation (https://www.frac.info/).

Ranman (cyazofamid, FRAC code 21) was effective in some experiments. It was effective when tested alone or tank mixed with ProPhyt in Illinois and in Florida (Babadoost and DeYoung 2012; Raid 2008e, 2008f, 2008h) and tested alone in New Jersey (Homa et al. 2014). It was among the most effective (Raid 2008f). Ranman is

Table 6. Efficacy of fungicides for managing downy mildew in basil in 2015

	Downy mildew incidence (% leaves with symptoms)[x]				Defoliation (%)[x]	
Treatment and rate/ha (application dates)[w]	**24 Aug**	**17 Sep**	**28 Sep**	**AUDPC[y]**	**31 Aug**	**17 Sep**
Nontreated control	79.3 a	90.5 a	89.5 ab	2,969 a	62.5 a	88.8 ab
F9177-1 364 g (1–6)	69.5 a	91.3 a	97.3 a	3,008 a	57.5 ab	88.8 ab
A20941A (oxathiapiprolin) 120 ml + Revus 402 ml (1,5), Quadris 876 ml (2,4,6), Revus 584 ml (3)[z]	37.3 ab	78.5 a	90.5 a	2,607 ab	16.3 bc	57.5 c
Revus 584 ml (1,5), Quadris 876 ml (2,4,6), A20941A 120 ml + Revus 402 ml (3)[z]	12.5 b	83.3 a	91.8 a	2,128 bc	7.5 c	55.0 c
Quadris 876 ml (1,3,5), A20941A 120 ml + Revus 402 ml (2,6), Revus 584 ml (4)[z]	42.5 ab	22.5 b	76.0 b	1,810 c	20.0 bc	60.0 bc
Quadris 876 ml (1,3,5), Revus 584 ml (2,4,6)[z]	58.8 ab	86.3 a	95.0 a	2,959 a	35.0 abc	80.0 abc
Ranman 201 ml (1,3,5), Revus 584 ml (2,4,6), K-Phite 2,338 ml (1–6)[z]	57.0 ab	84.5 a	95.0 a	2,927 a	32.5 abc	76.3 abc
Cueva 3,784 ml (1–6)	70.8 a	91.3 a	96.0 a	3,076 a	55.0 ab	93.8 a
Treatment *P* value	0.005	<0.0001	0.001	<0.0001	0.001	0.0004

[w] Rate of formulated product/ha. Application dates were as follows: 1 = 28 Jul; 2 = 7 Aug; 3 = 12 Aug; 4 = 25 Aug; 5 = 1 Sep; and 6 = 8 Sep.
[x] Numbers in each column with a letter in common are not significantly different from each other (Tukey's HSD, $P = 0.05$).
[y] AUDPC = area under the disease progress curve.
[z] Induce, a nonionic surfactant, was used at 0.125% with every application.

Table 7. Efficacy of fungicides for managing downy mildew in basil in 2016

	Downy mildew incidence (% symptomatic leaves in plot)[w,x]				
Treatment and rate/ha[v] (application dates)	**22 Aug**	**2 Sep**	**8 Sep**	**15 Sep**	**AUDPC[y]**
Nontreated control	2.7 a	46.0 a	84.3 a	87.0 a	1,260.8 a
F9177-1 364 g (2–8)	1.6 ab	4.6 b	47.4 b	71.4 a	599.1 b
Ranman 201 ml[z] (2,4,6,8), Revus 584 ml[z] + K-Phite 2,338 ml (3,5,7)	0.3 b	1.3 c	8.8 c	15.1 b	122.4 c
A21723E (oxathiapiprolin + mefenoxam) 1,000 ml (1), Revus 584 ml[z] (2,4,6,7,8), ProPhyt 4,675 ml (3,5)	0.3 b	0.0 d	0.2 c	1.0 c	7.8 d
Ridomil Gold SL 1,168 ml (1), Orondis Ultra 401 ml[z] (2,5,8), Revus 584 ml[z] (3,6), ProPhyt 4,675 ml (4,7)	0.5 b	0.0 d	0.1 c	0.2 c	3.8 d
Ridomil Gold SL 1,168 ml (1), ProPhyt 4,675 ml (2,5,8), Orondis Ultra 401 ml[z] (3,6), Revus 584 ml[z] (4,7)	0.5 b	0.0 d	0.0 c	0.2 c	3.5 d
Ridomil Gold SL 1,168 ml (1), Revus 584 ml (2,5,8), ProPhyt 4,675 ml (3,6), Orondis Ultra 401 ml[z] (4,7)	0.2 b	0.0 d	0.0 c	0.0 c	1.8 d
Treatment *P* value	0.001	<0.0001	<0.0001	<0.0001	<0.0001

[v] Rate of formulated product/ha. Soil drench application date was 21 Jul (date 1). Drip irrigation was run afterward to mimic a chemigation application. Application dates were as follows: 2 = 22 Jul; 3 = 28 Jul; 4 = 4 Aug; 5 = 11 Aug; 6 = 18 Aug; 7 = 25 Aug; and 8 = 31 Aug.
[w] Numbers in each column with a letter in common are not significantly different from each other (Tukey's HSD, $P = 0.05$).
[x] Some data were square-root transformed before analysis. Table contains de-transformed means.
[y] AUDPC = area under the disease progress curve.
[z] Ranman, Revus, and Orondis Ultra were applied with Induce (nonionic surfactant) 0.125% v/v.

registered for managing downy mildew in basil in the United States. Tolerances for residues are 90 ppm for fresh leaves and 144 ppm for dried leaves. Mode of action is to inhibit mitochondrial complex III, which affects multiple stages of fungal development, in particular sporulation (https://www.frac.info/).

Revus (mandipropamid, FRAC code 40) was effective in some experiments. It was effective when tested alone or tank mixed with ProPhyt (Babadoost and DeYoung 2012; Raid 2008e, 2008f, 2008h) and tested alone in New Jersey (Homa et al. 2014). It was the most effective fungicide in experiments conducted there in 2010, providing better control than Presidio, Ranman, Quadris, and Nutri-Phite (Raid et al. 2011a, 2011b). Forum, another fungicide with a related active ingredient, was also effective (Babadoost and DeYoung 2012; Raid 2008b, 2008d, 2008e, 2008f). They were among the most effective (Raid 2008f). Only Revus is registered for managing downy mildew in basil in the United States. Tolerances for mandipropamid residues are 30 ppm for fresh leaves and 200 ppm for dried leaves. This fungicide targets H5 cellulose synthase involved in cell wall biosynthesis (https://www.frac.info/).

Zampro (ametoctradin, FRAC code 45, and dimethomorph, FRAC code 40) was one of the two most effective fungicides. Zampro was effective when tested in Florida as BAS 651 F (Raid 2011a; Raid and Sui 2011a). Efficacy was improved when applied with an adjuvant (Silwet), and at the label rate (420 ml/ha) it was as effective as Revus plus Silwet (Raid and Sui 2011a). Zampro was also effective in subsequent experiments in Florida (Raid and Sui 2011b; Raid et al. 2013) and in Illinois (Babadoost and DeYoung 2012). This fungicide is not registered for managing downy mildew in basil in the United States, but it is labeled for downy mildew in brassica leafy vegetables, bulb vegetables, cucurbits, and leafy vegetables.

In conclusion, downy mildew can be effectively managed in basil with conventional fungicides. They should be applied frequently (e.g., weekly) starting before symptoms are found using application equipment designed to provide thorough spray coverage to plants. Alternation among products is needed to comply with label restrictions for managing fungicide resistance development. *P. belbahrii* has developed resistance so far only to mefenoxam (Cohen et al. 2013; Collina et al. 2016). Additionally, applying several fungicides in alternation to a crop ensures residues of each will be low at harvest. Mode of action and label use restrictions should be considered when developing a fungicide program. Reason can be applied four times with no consecutive applications of it or another FRAC code 11 fungicide (e.g., Quadris). Quadris can be applied six to 15 times depending on rate with no more than two consecutive applications. Ranman can be applied nine times with no more than three consecutive applications, which must be followed by the same number of applications of other fungicides. Revus can be applied four times with no more than two consecutive applications. Resistance management restrictions for Presidio require it be tank mixed with another fungicide labeled for this disease that has a different mode of action; rotation with other chemistry is recommended in the general resistance management section of its label. Applying these with a phosphorous acid fungicide has been documented to increase efficacy. There are no label restrictions on number of applications of phosphorous acid fungicides. Among all these fungicides, Revus has been the most effective in efficacy experiments, whereas Presidio and phosphorous acid fungicide have been the least effective. Fungicide programs consisting of an alternation among Quadris, Ranman, and Revus, each applied with a phosphorous acid fungicide (ProPhyt) or not, were consistently effective in Illinois (Babadoost 2019; Babadoost and DeYoung 2013; Babadoost and Sulley 2018).

Acknowledgments

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