Lima Bean Downy Mildew: Impact, Etiology, and Management Strategies for Delaware and the Mid-Atlantic Region, U.S.

Lima bean (*Phaseolus lunatus* L.) has been an important crop grown for canning and freezing in the mid-Atlantic area of the United States since the nineteenth century (39). Three commercial classes of lima bean are used for processing: the small-seeded green baby lima, the small-seeded speckled lima, and the large-seeded Fordhook lima (Fig. 1). The green baby lima class comprises the vast majority of production in Delaware. Morphological, biochemical, and molecular evidence indicate at least two, and possibly three, sites of domestication of the lima bean in Central and South America (30,31). The green baby and speckled lima classes derive from the Mesoamerican gene pool, whereas the Fordhook lima class derives from the Andean gene pool (49).

In 2005, lima bean grown for processing was planted on 6,475 hectares in Delaware, with production valued at \$6,475,000 (55). In that same year, 13,211 hectares of lima bean were grown in the United States, with California being the largest producer of lima bean and Delaware being second (1). Lima bean is considered to be the cornerstone crop of the vegetable processing industry in Delaware, and Delaware remains one of the few states that produce the crop (41).

In the mid-Atlantic states, lima bean is grown using conventional tillage practices and is planted in 76-cm rows, generally after pea or small grain in June or July. Growers contract with processing companies for a certain acreage to be planted, and in most cases, the processing company performs the harvest mechanically using pod-stripper combines. Improvements to harvesters in recent years, including multi-beater threshers and electrohydraulic sys-

tems, have increased the harvest recovery efficiency of the stripper heads for the one field pass harvesting process. Yields in Delaware generally increase with later planting dates, which are associated with higher rainfall and cooler days and nights in September and October, a time when these plants are flowering and setting pods (68). Depending on cultivar, flowers first form 35 days after planting, and peak flowering occurs at 60 days. Harvest occurs 80 to 90 days after planting for baby lima bean and 90 to 100 days after planting for Fordhook cultivars. While late planting dates result in fall flowering and a concomitant increase in yields under normal circumstances, environmental conditions in fall produce evening dews and leaf wetness that provide ideal conditions for the development of downy mildew caused by *Phytophthora phaseoli* Thaxter.

History of Lima Bean Downy Mildew

Lima bean downy mildew was first reported by Thaxter in Connecticut in 1889 (60), and we continue to detect *P. phaseoli* in Delaware almost every growing season (29). Other published reports include detection in the Philippines (6), the former Soviet Union (57), Congo (now Zaire) (32), Puerto Rico (33), and Italy (5). Overseas reports of lima bean downy mildew

have not occurred in recent years and have not been substantiated. Currently, *P. phaseoli* is limited to the mid-Atlantic areas of Delaware, Maryland, and New Jersey and has never been reported to occur in California. This is likely to be due, at least in part, to California's lower humidity compared with the eastern United States.

In 1889, Thaxter (60) was the first to report *P. phaseoli* causing a new disease, downy mildew of lima bean, in Connecticut, and the pathogen was first found infecting lima bean in Delaware by Smith in 1904 (56). In 1958, *P. phaseoli* was responsible for an epidemic, with more than 907,185 kg of bean loss from 4,725 hectares in Delaware (3). In 2000, race E of *P. phaseoli* was responsible for an epidemic in Delaware during September and October, which resulted in an estimated production loss of 40%, equal to a farm value loss of \$3,000,000 (E. Kee, *personal observation*).

Host Range and Distribution of the Pathogen

Hosts of *P. phaseoli*, in addition to lima bean, may play an important role in overwintering of the pathogen and the development of downy mildew on lima bean. Plant species other than *P. lunatus* have been reported to be hosts for *P. phaseoli*. In 1925, Leonian (43) reported that he iso-

Fig. 1. Comparison of commercial classes of lima bean (*Phaseolus lunatus*) used by the vegetable processing industry; large-seeded Fordhook (left), small-seeded baby green lima bean (right), and small-seeded speckled lima bean (center).

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Fig. 2. Signs and symptoms of lima bean downy mildew caused by *Phytophthora phaseoli*: A, healthy flower racemes; B, infected flower racemes; C, close-up of typical cottony mycelium and sporangia on flat pods.

lated *P. phaseoli* from *Phaseolus vulgaris* (navy bean) in West Virginia. Leonian did not report morphometric information about his isolate, so we cannot be certain of its identity.

In 1928, Clara (6) reported that an isolate of what was characterized as *P. phaseoli* produced varying levels of seedling infection and disease in eight plant species including *Brassica juncea* (L.) Czerniak (brown mustard), *Hevea brasiliensis* (H.B.K.) Muell. Arg. (para rubber), *Lycopersicon esculentum* L. (tomato), *Phaseolus* spp. (bean), *Raphanus sativus* L. (radish), *Sandoricum indicum* Cav. (santol), *Solanum melongena* L. (eggplant), and *Vigna unguiculata* subsp. *sesquipedalis* (L.) Verd. (sitao). All of the above “hosts” were reported to have infection confined to wounds, or produced slight rotting or damping-off of stems. However, the conditions used to produce infection were not stated. Since Clara (6) failed to provide information on the conditions used to promote disease development or detail symptom development and because of the limited and slightly different morphometric data provided for the isolate, we lack confidence that the isolate used was *P. phaseoli* and that the species reported were hosts. Clara (6) reported that the sporangia of the Philippine isolate averaged $35.7 \times 25.2 \mu\text{m}$. This is somewhat different from our reported sporangial measurements of $39 \times 22 \mu\text{m}$. Clara does not mention the length of sporangial pedicels for the isolate used. Pedicel length is an important morphological characteristic differentiating this *Phytophthora* species from others.

In 1951, Hyre and Cox (37) tested crop species for susceptibility to *P. phaseoli*, including *P. lunatus*, *L. esculentum*, and *P.*

vulgaris, and found that only *P. lunatus* was susceptible, producing white downy growth of the pathogen. In 2002, Dominiak (21) carried out an extensive study of agricultural crops and weed species as alternate hosts of *P. phaseoli*. Of the 33 plant species, including *L. esculentum*, *P. vulgaris*, and *R. sativus*, and 20 weed species tested, only *P. lunatus* and *P. limnensis* (now regarded as *P. lunatus*) became infected.

Development of Disease and Symptom Expression

While the initial infection process of lima bean in the field is still unclear, flower racemes, shoot tips, petioles, small pods (pins) to mature pods of lima bean are the most susceptible plant organs (Figs. 2 and 3). In dew chamber studies, both hypocotyls and leaves are susceptible, but they play little role in disease progress in the field. Under ideal environmental conditions, pods are covered with white, cottony mycelial growth with abundant sporangia (Fig. 2), with a reddish band often surrounding the infected area (Figs. 2 and 4A). Infected pods become necrotic, dried, and eventually shrivel (Fig. 5). These symptoms may be used to distinguish *P. phaseoli* infections from the newly reported pathogen of lima bean, *Phytophthora capsici* (20), which produces no red margin. Mycelia and sporangia are more tightly appressed to the pods with *P. capsici* (Fig. 4B).

Pathogen Description

Phytophthora phaseoli was first described by Thaxter (60), amended by Clinton (7), and was described in Erwin and

Fig. 3. Signs and symptoms of downy mildew of lima bean caused by *Phytophthora phaseoli* on petiole and shoots.

Ribeiro (27). *P. phaseoli*, as we have observed it, differs from the original description by Thaxter in 1889, which also is the basis for the description in Erwin and Ribeiro. (Note that there is a typographical error in Erwin and Ribeiro for the average sporangial dimensions.) The primary difference is in the length of the pedicel, which ranges from 1 to 5 μm for *P. phaseoli*, but is described by Thaxter as ranging from 5 to 20 μm . The sporangiophores are mostly simple, not sympodially branched. This could lead to some confusion and

misidentification with *P. capsici*, which has a longer pedicel length and sporangio-phores described as sympodially branched. Oospores are not produced abundantly on host tissue; rather, they are produced rarely or in response to fluctuations in temperature or drying of host tissue. Mycelium is branched, with no hyphal swellings or chlamydospores.

Sporangia are semi-papillate, oval to limoniform to elliptical with a truncate base consisting of a short pedicel (Fig. 6A). On lima bean tissue, sporangia average $39 \times 22 \mu\text{m}$ with a range of 33 to 48×18 to $28 \mu\text{m}$, with an average length:width ratio of 1.8:1. On lima bean agar, sporangia are

slightly smaller, averaging $34 \times 22 \mu\text{m}$. The average length of the pedicel is $2.75 \mu\text{m}$ with a range of 1 to $5 \mu\text{m}$. Simple sporangio-phores average $310 \mu\text{m}$ with a range of 140 to $525 \mu\text{m}$. Sporangia are formed by swelling at the apex of the sporangio-phore. A septation is formed when a sporangium is completely formed, resulting in release of the sporangium with the short pedicel where the attachment had been (Fig. 6A). Sporangia are caducous or deciduous, and direct germination is common, although zoospores may be produced and released. Sporangia are commonly found on agar as well as on plant tissue (Fig. 6B) and may be airborne or waterborne due to the cadu-

cous nature and short pedicel. *P. phaseoli* is homothallic with amphigynous antheridia. Oospores are formed in old culture plates and on plant tissue, but are not numerous.

Growth of isolates in culture is 6 to 9 mm per week at 18 to 20°C on frozen lima bean agar (4). A typical culture will grow radially 18 to 20 mm in 21 days from a mass transfer. Isolates do not survive long-term on agar plates, but survive several years in screw cap test tubes of sterile water containing autoclaved corn seed, hemp seed, or cucumber seed. Frozen lima bean agar is best for growth of isolates and sporangial production for inoculum. The optimum temperature for growth is 15 to 20°C , but growth slows below 5°C or above 30°C . Temperatures greater than 30 to 32°C may be lethal to the fungus (38). However, isolates of some races of the fungus survived temperatures of 35 to 38°C (19).

Description of Physiological Races

Downy mildew has been a major disease of lima bean grown in the humid eastern United States since the late 1880s. Presently, six physiological races of *P. phaseoli*, A, B, C, D, E, and F, are known to exist (19). A physiological race, hereafter referred to simply as race, is a subdivision of a pathogen species, particularly fungi, distinguished from other members of the species by specialization for pathogenicity in different host cultivars (42). The development of new races of *P. phaseoli*, and the epidemics that they have produced in the eastern United States, has been a major factor in the relocation of lima bean grow-

Fig. 4. A, Lima bean downy mildew caused by *Phytophthora phaseoli*, and B, lima bean pod blight caused by *P. capsici*. Note the cottony nature of mycelium and reddening of pods infected by *P. phaseoli* and the granular sugarlike appearance of mycelium on pods infected by *P. capsici*.

Fig. 5. Effect of *Phytophthora phaseoli* infections on lima bean pod production and color. A, Infected pods showing various degrees of drying and necrosis. B, Effect of *P. phaseoli* infections on yield from 10 feet of row of lima bean. Fewer, dry, discolored, and shriveled pods from infected plants (left, unsprayed control), and pods from healthy plants (right, sprayed with Ridomil Gold/Copper).

ers and processors from Connecticut and New York to New Jersey, then to Delaware and Maryland (39).

Until 1958, one race, later designated A (67), was the only known race of the pathogen. In 1958, a second race of *P. phaseoli*, designated B, was isolated from the lima bean cultivar Thaxter in New Jersey (63). In 1969, race C was isolated from the lima bean cultivar Dover in New Jersey near the site of previous epidemics caused by race B (64). Race D of *P. phaseoli* was first detected in 1975 from lima bean in experimental plots in Beltsville, MD (61) and in Delaware in 1990 (T. A. Evans, *personal observation*). In 1995, race E was first detected in Delaware (28) and became the dominant race of the pathogen in the region by 2000 (19).

In 2000, race F was first detected in Delaware and Maryland (28), and by 2004 it had become the dominant race (29). Races A, B, C, D, E, and F of *P. phaseoli*, and the cultivars used to differentiate them, have been clarified by Wester (64), Thomas and Blount (61), Stavely (58), Kee et al. (41), and most recently by Davidson (19). The existing races can be differentiated by determining the susceptibility of five baby lima bean cultivars (Table 1).

Survival and Dissemination of the Pathogen

P. phaseoli has been reported to overwinter as oospores on infected lima bean refuse in the field but not as hyphae or sporangia (66). The pathogen is not known to be seed transmitted (8). Therefore, oospores of *P. phaseoli* are the most likely primary inoculum, with the secondary inoculum being sporangia (8). Oospores may produce germ tubes and infect the plant directly or may produce sporangia. Sporangia may produce germ tubes and directly enter the plant or produce motile zoospores that may be released to infect susceptible lima bean tissues (62). The sporangia are airborne and are released daily over a 3- to 4-h period, midday (54), with symptoms appearing about 7 to 10 days after infection.

Measures for Disease Management

Measures to manage downy mildew have focused on prediction of disease occurrence, chemical control, and resistance. In 1958, Hyre (36) developed a predictive model using temperature and rainfall to alert lima bean growers in the mid-Atlantic region when conditions were favorable for downy mildew. According to Hyre's model, which was one of the first forecasting models for plant epidemics in the United States, conditions were favorable when there were 7 days of mean temperature of <26.1°C (79°F) but >7.2°C (45°F), with a 7-day total rainfall of >3.05 cm (36). However, less rain was required if there had been periods of heavy dew. If the

criteria were met for seven consecutive days, a fungicide spray alert was issued because downy mildew was possible in 1 to 2 weeks. According to Hyre, the cycle was broken if temperatures exceeded 32.2°C (90°F).

Recent studies indicate that races E and F may be more tolerant to temperature extremes than races A or B, with which Hyre would have worked (19). Races E and F appear to be capable of surviving temperatures as high as 35 to 38°C, although comparisons are impossible, as isolates of races A, B, and C are no longer evident in the population (28). A leaf wetness duration of 4 to 6 h with concomitant nighttime temperatures of 15 to 20°C for as few as 5 days may provide ideal conditions to predict disease development (54).

The use of resistant cultivars remains the most cost effective method of managing downy mildew. Planting disease-resistant cultivars of baby lima bean has been the primary disease control strategy since 1948, when a lima bean breeding program for developing resistance to the downy mildew fungus was initiated in cooperation with the Long Island Vegetable Research Farm at Riverhead, NY (65). Early crosses to incorporate disease resistance into 'Early Thorogreen' and 'Fordhook 242' were made at the USDA Plant Industry Section, Beltsville, MD, in the spring of

1949. These initial crosses resulted in the introduction of Thaxter in 1959, the first lima bean cultivar with resistance to *P. phaseoli*, race A (67). The evaluation of commercial lima bean cultivars for their reactions to *P. phaseoli* inoculations in the field has been carried out at the University of Delaware for many years. Recently, these evaluations have focused on races E and F, and resistance to both has been confirmed in commercial baby lima bean cultivars and accessions (50–53). The cultivars Cypress, 184-85, and C-elite Select are known to be resistant to race E, and cultivars Maffei-15 (M-15), Eastland, and 8-78 are resistant to race F. Unfortunately, no single commercial lima bean cultivar has been identified with resistance to both race E and F. The speckled bean 'Jackson Wonder', which is commonly grown commercially in Delaware, lacks resistance to all races of *P. phaseoli*.

In 2004, lima bean breeding was re-initiated at the University of Delaware. Results from test cross inoculations indicate that the resistance to race E of *P. phaseoli*, carried by the cultivars Cypress and Dover Tucker, is conferred by the same single dominant gene (26), and complete resistance to race F carried by Maffei 15 and 'B2C' also is conferred by a single dominant gene. Both of these cultivars also carry some partial resistance to race F,

Fig. 6. Photomicrographs of sporangia of *Phytophthora phaseoli*. Image A (×630) shows one sporangium attached to its sporangiophore and the characteristic shape and very short pedicel of a detached sporangium. Image B (×200) shows simple sporangiophores with sporangia attached on a leaf surface.

Table 1. Cultivar differential for determination of races of *Phytophthora phaseoli*

Cultivars	Races of <i>P. phaseoli</i> ^a					
	A	B	C	D	E	F
Thaxter	R ^b	S	S	S	S	S
Bridgeton	R	R	S	R	R	S
8-78	R	R	R	R	S	R
184-85	R	R	R	S	R	S
M-15	R	R	R	R	S	R

^a Physiological races of *P. phaseoli* are distinguished by their ability to infect different cultivars of *Phaseolus lunatus*.

^b Reactions of isolates of *P. phaseoli* on different cultivars with R = resistant or no infection and S = infection and the development of cottony mycelium and sporangia.

which seems to be conferred by either of two recessive resistance genes. It is likely that Maffei 15 and B2C carry the same resistance genes, since Maffei 15 is a selection from B2C (26).

Fungicide testing for control of downy mildew of lima beans began as early as 1897 when Bordeaux mixture was recommended for control (59). Later testing included copper fungicides and some of the organic fungicides (ferbam, Spergon, Phygon, Dithane D-14 plus zinc-sulfate and lime) (10). Copper was the preferred fungicide in the early days for control of downy mildew on Fordhook lima bean, but when 'Henderson Bush' (baby lima bean) became the primary cultivar grown in the mid-Atlantic area, it became evident that this cultivar was sensitive to copper fungicides. Phytotoxicity became such a serious problem that recommendations warned against using copper fungicides when disease levels were low to avoid yield losses associated with copper applications. The exception to that recommendation was when downy mildew threatened to become a serious problem late in the fall crop (2). By 1950, it was obvious that a new fungicide that did not damage the crop was needed to control downy mildew. Crossan et al. (9) reported success in controlling downy mildew without phytotoxicity with maneb or tri-basic copper sulfate when applications were timed with a disease forecast. Maneb became the industry stan-

dard until 1989 when all of the EDBC fungicides were re-registered under the Federal Insect, Fungicide and Rodenticide Act (FIFRA), and lima bean was removed from the label. This action resulted in only copper fungicides being labeled for downy mildew. During the period when maneb and mancozeb were undergoing re-registration review, testing was initiated to determine efficacy of available fungicides for downy mildew control (44-46). Copper hydroxide fungicides were available in addition to chlorothalonil and metalaxyl. However, there were hindrances to obtaining labels for both those products for a minor crop such as lima bean, when the disease occurred in the relatively small mid-Atlantic area on only 6,070 hectares of late-planted lima beans. By the time re-registration occurred in 1989, disease-resistant cultivars were effective and downy mildew was not an issue. Copper hydroxide was determined to be more effective than tri-basic copper sulfate (22,23) and became the only additional labeled fungicide that could be used to control downy mildew.

By 1998, it was clear that a new race of *P. phaseoli* had developed, genetic resistance was being overcome, and downy mildew was once again a problem. Fungicide testing was re-initiated at the University of Delaware to look at new fungicides for control of downy mildew. Early testing with metalaxyl (44-46) demonstrated that

it was effective, so the new formulation of mefenoxam was included in subsequent tests along with new formulations of copper hydroxide and other copper compounds, strobilurin fungicides, and new fungicides with efficacy on oomycete fungi (Table 2). Of the products tested, mefenoxam, phosphorous acid salts, dimethomorph, pyraclostrobin, and azoxystrobin were the most efficacious. Table 3 is a compilation of the effective products tested to date and the number of years they were tested. As a result of our testing and cooperation with the USDA's IR-4 Project that supports the registration of fungicides for minor crops such as lima bean, a 24 (c) state special local needs registration was obtained in 2004 for the use of mefenoxam copper (Ridomil Gold/Copper, Syngenta Crop Protection) for control of lima bean downy mildew in Delaware and Maryland. Mefenoxam was labeled as an in-furrow or banded application at planting for *Pythium* damping-off, but the lack of residue data for mefenoxam applied to foliage did not permit registration for foliar application for downy mildew. Since the Environmental Protection Agency (EPA) would not accept the metalaxyl residue data, IR-4 in cooperation with Syngenta Crop Protection generated the residue data required for mefenoxam tolerance. Unfortunately, rates of Ridomil Gold or Ridomil Gold PC Granules applied at planting that were not

Table 2. Effective fungicides for control of downy mildew of lima bean, caused by *Phytophthora phaseoli*, based on fungicide testing from 1998 to 2006

Fungicide	Common chemical name	FRAC grouping ^a	Number of successful tests (total number of times tested) ^b
Ridomil Gold Copper ^{**c}	Mefenoxam/copper hydroxide	Group 4 + M1	8 (8)
Phostrol ^{**}	Phosphorus acid salts	Group 33	6 (6)
Champ DP, Kocide DF ^{**}	Copper hydroxide	Group M1	7 (8)
Cuprofix Dispers ^{**}	Basic copper sulfate	Group M1	1 (1)
Quadris	Azoxystrobin	Group 11	4 (6)
Headline (Cabrio, BAS500)	Pyraclostrobin	Group 11	3 (5)
Forum (Acrobat)	Dimethomorph	Group 15	1 (2)

^a FRAC = Fungicide Resistance Action Committee. Group M1 = multisite/inorganics, Group 4 = Phenylamide, Group 11 = QoI, Group 15 = Cinnamic acid, Group 33 = Phosphonates.

^b A successful test is defined as one in which the fungicide treatment resulted in significantly better control than the check or yields were significantly higher than the check. In 2002, preventative and curative tests were conducted but the disease never developed, resulting in no data for that year, which is not included in this column.

^c ^{**} Currently labeled for downy mildew control through a Sec 3 (national use) or 24 (c) (special local need) label.

Table 3. Recommendations for fungicide applications, rates, and timing of application for downy mildew of lima bean caused by *Phytophthora phaseoli* in the mid-Atlantic States, U.S.

Fungicide	Preventative		Curative ^a	
	High disease	Low disease	High disease	Low disease
Ridomil Gold/Copper	2 lb 2× 7-14 day interval	2 lb 1×	2 lb 2× 7-14 day interval	2 lb 1-2× 10-14 day interval
Phostrol	3-4 pt 1-2× 7-14 day interval	2-4 pt 1-2× 7-14 day interval	3-4 pt 2× 7-14 day interval	4 pt 1× or 2-4 pt 2× 7-14 day interval
Copper	2 lb 4× 7-day interval	2 lb 2× 7-10 day interval	Not recommended	Not recommended

^a Curative applications were initiated when disease was at very low incidence, less than 1% of pods and/or racemes infected.

phytotoxic also did not provide season-long protection against downy mildew infection (23,24,44,46). Following field testing with phosphorus acid salts (Phostrol, Nufarm Agriculture, USA) by Davey et al. (14,16), Phostrol was also granted a 24 (c) registration for control of downy mildew in 2004. Currently, mid-Atlantic lima bean growers have the option of selecting copper fungicides, Ridomil Gold/Copper, or Phostrol for downy mildew control (40). Testing is continuing to refine rates and timing of phosphorus acid salts for effective control under varying environmental conditions.

The timing and number of fungicide applications for downy mildew control have always been important to growers to obtain maximum economic control. Testing conducted in 1948 demonstrated that downy mildew could be controlled with five weekly applications of Bordeaux mixture, tri-basic copper sulfate, Dithane Z-78, or Parzate (zineb) after the disease had appeared in the field (34). In 1950, Heuberger et al. (35) recommended weekly fungicide applications for as long as weather conditions remained favorable for infection. This usually required at least two applications to significantly reduce the number of infected pods. The development of the Hyre forecasting model (36) allowed growers and processors to predict periods favorable for downy mildew. Scouting was usually initiated at that time, and fungicide applications were delayed until the first symptoms of downy mildew were detected. Scouting large areas for a disease that only infects pods usually hidden by a dense canopy of healthy leaves sometimes resulted in undetected disease establishment, and often fungicides were unable to provide control in weather favorable for disease development. Growers used their best judgment by using the forecasting model and weather forecasts to time sprays, knowing the risk of not detecting the disease in a timely manner.

Fungicide testing for control of downy mildew of lima bean at the University of Delaware has had two objectives: (i) identify efficacious materials (11,16,22–24,44–46,48), and (ii) determine the most effective timing of their application (12–15,17,47,48). Our field studies have been done by inoculating lima bean plants in the field with specific races of the pathogen and providing ideal conditions for infection and disease development by exposing plants to prolonged dew periods created by timed overhead misting. By these actions, we greatly increase infection and disease incidence and have demonstrated that control of downy mildew can be achieved by either preventative or curative applications of efficacious fungicides provided the latter is made when the disease is first observed. The recommendations included in Table 3 are the result of our testing program to date and have been presented to

the industry in extension meetings and publications (40). Growers currently make preventative applications of copper fungicides either alone or in combination with insecticides for pod-feeding insects. When conditions for downy mildew are favorable and outbreaks occur, applications of Ridomil Gold/Copper (mefenoxam) or Phostrol are made curatively to unsprayed fields or those where copper fungicides have been applied preventatively. Phostrol and Ridomil have been shown to be effective as early curative treatments but are recommended as preventative treatments. The risk of resistance development exists for Ridomil but not for Phostrol. Since Ridomil Gold/Copper contains copper hydroxide, which is active for control of downy mildew, two consecutive applications can be made but no more than two. Growers with downy mildew infected fields also have the option of using Phostrol exclusively or Ridomil Gold/Copper alternated with Phostrol to reduce the possibility of developing resistant strains of the fungus. No more than two sprays with mefenoxam would be needed in most seasons if applied at the first sign of disease, thus reducing selection pressure and resistance development.

Current Status and Future Outlook

Changes in the race of *P. phaseoli* have resulted in numerous epidemics over the past 100 years. Over the 20-year period from 1975 to 1994, the dominant race of *P. phaseoli* was D, and few large epidemics occurred in the mid-Atlantic region because of the availability of resistant cultivars. In the 5-year period from 1995 to 2000, two new races (E and F) were detected and became dominant in succession. This rapid change of race resulted in large epidemics and great economic losses to the industry. It is likely that the shifts in the dominant race were largely due to the changes in cultivars planted by growers over the same period. The development of additional races is a constant threat, and their monitoring is essential for the safety of the lima bean industry. While it is likely that *P. phaseoli* overwinters in the soil as oospores, the exact process by which the initial infection takes place each season is still unclear. Initial infections generally appear on flowers, young pods (pins), or larger, flat pods, but the process by which the pathogen progresses from an overwintering oospore in the soil to infection of the reproductive parts of the plant is not understood and needs to be clarified.

Currently, several fungicides are labeled and effective for control of downy mildew if applied in a timely manner. Ridomil Gold/Copper (mefenoxam/copper), Phostrol (phosphorus acid salts), and copper fungicides are currently labeled on lima bean and are effective. Other fungicides such as azoxystrobin and pyraclostrobin

are labeled for control of anthracnose and soybean rust. Both of these products have activity against downy mildew that is not included on the label, but they could be labeled for downy mildew through the FIFRA section 24 (c) process, if needed. Other oomycete fungicides are being developed for late blight on potato and cucurbit downy mildew, and these candidate fungicides may prove to be valuable in the future should they be needed for downy mildew control. Copper fungicides currently available are good protectant fungicides when disease pressure is low to moderate, and they are good tank mix partners with mefenoxam and in rotation with other fungicides to prevent fungicide resistance. It has also been demonstrated that some formulations of copper may be phytotoxic under certain environmental conditions, but they do not reduce yield (21). A high risk of mefenoxam resistance developing in *Phytophthora* exists. However, as few applications are made during the growing season and not all acres of baby lima bean are treated, the overall risk may be considered moderate for *P. phaseoli*, but resistance to mefenoxam has been documented in *P. phaseoli* (25). The risk for the development of resistance to phosphorus acid fungicides, such as Phostrol, is considered low by the Fungicide Resistance Action Committee (FRAC).

One goal of the current lima bean breeding program at the University of Delaware is to improve cultivar resistance to the dominant or emerging races of *P. phaseoli*, particularly to combine resistance to both E and F in commercially viable baby and Fordhook lima bean cultivars. Other goals must include increasing heat tolerance, improving plant habit with respect to suitability for mechanical harvest, and increasing yield in both baby and Fordhook lima beans. Meeting these goals will help ensure the future of the lima bean and vegetable processing industry in the mid-Atlantic region.

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