Anthracnose on Strawberry: Its Etiology, Epidemiology, and Pathology, Together with Management Strategies for Strawberry Nurseries: Introduction to the Workshop

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Abstract. In recent years, anthracnose fruit rot (AFR) caused by *Colletotrichum acutatum* J.H. Simmonds, has become an even more serious threat to strawberry plant and fruit producers in major strawberry-growing areas of North America. This highly virulent pathogen causes fruit rot, crown rot, root rot, and lesions on petioles and stolons. In fruit-production fields, the best way to control AFR is to prevent the introduction of the pathogen into the field by using anthracnose-free transplants. A critical step in controlling the disease then, lies in effective nursery management practices. Participants in this workshop outlined several key management strategies, including methods to eliminate pathogen inoculum, cultural practices that reduce host plant susceptibility, and chemical and biological control measures. Industry members stressed the importance of giving research priority to developing improved methods of nursery field sampling and detection of *C. acutatum* in asymptomatic plants with latent infection. Being able to rapidly and economically diagnose *C. acutatum* in symptomless plant material at each step in the multiyear nursery plant propagation cycle (foundation, registered, and certified plants), will help nursery growers minimize the potential of selling *C. acutatum*-infected transplants to fruit growers. A video recording of the 4-h workshop was produced by ASHS Video Workshop Series (<http://ashs.org/resources/videoworkshopseries.html>).

On 18 July 2004, a workshop was held at the ASHS Annual Meeting in Austin, TX, for the purpose of considering the different dimensions of a growing problem that commercial nurserymen in North America are having in controlling strawberry plant infections by anthracnose fruit rot (AFR), caused by *Colletotrichum acutatum* J.H. Simmonds. The workshop took advantage of the knowledge and experience of nine industry, government, and research experts from North America (representing a geographic cross-section of the major strawberry-production regions in the United States and Canada), and a researcher from Israel, Dr. Stanley Freeman, Department of Plant Pathology, ARO, The Volcani Center, who is internationally recognized for his expertise of the fungus *Colletotrichum*, one of the most important genera of strawberry pathogens in the world (Casado-Diaz et al., 2006).

The idea to organize this workshop first came from discussions among scientists and industry members at the Centennial Conference of ASHS in Providence, RI, where in business meetings of the Viticulture and Small Fruit Working Group (3 Oct. 2003), as well as the Industry Division (5 Oct. 2003), concerns were registered that the AFR pathogen, *Colletotrichum acutatum*, was becoming an increasingly serious disease affecting North American strawberry nurseries and fruit growers. Similar discussions took place at the professional meeting of NCCC-022, Small Fruit and Viticulture Research Group, in late Oct. 2003, and at this meeting a decision was made by Adam Dale, Dan Legard, Tom Sjulín, and myself to proceed with the organization of a workshop for the

ASHS Annual Conference in July 2004 in Austin, TX. The 4-h workshop on 18 July 2004, was divided into two parts: 1) Etiology, Epidemiology, and Pathology of Anthracnose on Strawberry; and 2) Anthracnose Management Strategies for Strawberry Nurseries, with particular emphasis on the AFR caused by *C. acutatum* J.H. Simmonds. The workshop also received sponsorship from the California Strawberry Commission (CSC), Driscoll Strawberry Associates (DSA), Arkansas Strawberry Growers Association, North American Strawberry Growers Association, Ontario Berry Growers Association, and the North Carolina Strawberry Association, Inc. The support from these organizations made it possible for organizers to invite Dr. Stanley Freeman to the workshop in Austin.

WRITTEN PROCEEDINGS

The four oral presentations in Austin that were subsequently developed into papers for the workshop proceedings include 1) Epidemiology and Pathology of Strawberry Anthracnose: A North American Perspective (Barbara J. Smith); 2) Management, Survival Strategies, and Host Range of *Colletotrichum acutatum* on Strawberry (Stanley Freeman); 3) The Role of Micropropagation in Producing Specific Pathogen-tested Plants (Adam Dale, Becky R. Hughes, and Danielle Donnelly); and 4) Special Problems in Nursery Propagation of Day-Neutral Strawberry Cultivars Susceptible to *Colletotrichum acutatum* (Thomas M. Sjulín).

VIDEO PROVIDES A VALUABLE SUPPLEMENT TO WRITTEN PROCEEDINGS

The discussions in the workshop touched on a number of important subjects and issues,

many of which are not covered in the written proceedings. Consequently, the information contained in the video, *Anthracnose on Strawberry: Management Strategies for Plant and Runner Tip Nurseries* (available through the ASHS Video Workshop Series at <http://ashs.org/resources/videoworkshopseries.html>), provides a very valuable supplement to the written proceedings. The oral presentations from the workshop that do not appear in these written proceedings include

- 1) *Colletotrichum acutatum* in Florida strawberry, Jim Mertely, Dan Legard, Natalia Peres, Craig Chandler, and Teresa Seijo (CD # 1);
- 2) Special considerations regarding strawberry plugs and *Colletotrichum acutatum*, E. Barclay Poling (CD # 1);
- 3) Cooperative efforts by the California Strawberry Commission to control *Colletotrichum acutatum* in strawberry transplants, Dan Legard (CD # 2);
- 4) The importance of a certification program for strawberry production, Zvezdana Pesic-VanEsbroeck (CD # 2);
- 5) An effort to get the attention of researchers who work with *Colletotrichum acutatum*, Curt Gaines (CD # 2); and
- 6) Maintaining plant quality in strawberry propagation nurseries: a horticulturist's perspective, Kirk Larson (CD # 3).

All of the oral presentations given in Austin were recorded for the video proceedings with the exception of the talk by USDA researcher and plant pathologist, Dr. Barbara Smith.

The video should be of particular interest to researchers (especially breeders, plant pathologists, and molecular geneticists) who wish to "get inside" some of the complex challenges that North American strawberry nursery growers currently face in their efforts to produce disease-free plant material for a

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strawberry industry in the United States that required an estimated 928 million plants in 2003 (Table 1). Extension educators and crop consultants who advise commercial strawberry nurseries and fruit growers will particularly appreciate the information in the video provided by Kirk Larson, UC–Davis pomologist, who provides a practical perspective on how to maintain plant quality in strawberry-propagation nurseries, including hot water dips for nursery plant material. The video should also be useful to teachers of plant pathology, small-fruit production courses, as well as for extension-agent training programs. After viewing this video, a good follow-up exercise for agent trainers or classroom instructors is to have the students critique the actual production practices of the various strawberry nurseries in the United States and Canada that supply plant material to commercial fruit operations in their state, region, or province.

SETTING THE STAGE FOR THE WORKSHOP IN AUSTIN

To my knowledge, this was the first time that scientists and industry leaders from

across North America had actually come together to discuss AFR caused by *C. acutatum* in the context of trying to understand what could be done to reduce, if not eliminate, this pathogen from North American farms producing strawberry plants. For a workshop that had the primary goal of identifying *management strategies* to help nursery growers minimize the potential of selling disease-infected transplants to fruit growers, I believe we had the correct “mix of disciplines,” including four “active” plant pathologists (one from Israel) and two research directors who were previously trained in plant pathology. Among the four horticulturists represented, there was one strawberry breeder from Canada, two strawberry cultural research/extension workers (from California and North Carolina), and one nurseryman from California. Nursery grower Curt Gaines is a leader in the strawberry nursery industry in California, and an important contribution to this workshop was his candid analysis of how *C. acutatum* “may be” making its entrance into the nursery production system, as well as to request that researchers give high priority to developing improved methods of nursery field sampling and detection

of *C. acutatum* in asymptomatic plants with latent infection.

FRUIT-INDUSTRY SIZE AND ECONOMIC VALUE IN THE UNITED STATES

Many readers may be unaware that the United States is the largest producer of strawberries in the world, accounting for 28% of the world supply in 2004; the total value of U.S. strawberry production was valued at \$1.5 billion USD in 2004 (\$1.33 billion USD fresh; \$136 million USD processed), with California production valued at \$1.22 billion USD (83% of total) and Florida’s contribution, mainly of winter strawberries, accounting for 11.9% (\$178 million USD) (Boriss et al., 2006). Other significant production states in 2004 were North Carolina and Oregon, each worth \$15.8 million USD in 2004 (Boriss et al., 2006). Total harvested area in the United States was 20,882 ha (51,600 acres) in 2004, a record high over the last 25 years. California acreage has increased consistently over the last three and a half decades, increasing by 200% from 4452 ha (11,000 acres) in 1980 to 13,355 ha (33,000 acres) in 2004; meanwhile, Florida acreage has increased by 40% from 2023 ha (5000 acres) in 1982 to 2832 ha (7000 acres) in 2004 (Boriss, 2006). Production in California grew from 987 million pounds in 1990 to a record 1.96 billion pounds in 2004, and average yields were just under 67 MT/ha (30 tons per acre); meanwhile, Florida yields averaged 26 MT/ha (11.5 tons per acre) in 2004, which was a decrease from a high of 39 MT/ha (17.5 tons per acre) in 2000 (Boriss, 2006). In the period from 2000 to 2003, average yields per ha in North Carolina have fluctuated between 22 MT to 30 MT (10 to 13.5 tons per acre), and for the same period in Oregon yields have fluctuated between 22 and 29 MT/ha (10 and 13 tons per acre). In New York, with predominantly matted-row production, production area fluctuated between 567 and 648 ha (1400 and 1600 acres) in the period from 2000 to 2003, and average yields varied from 7 to 10 MT/ha (3.3–4.5 tons per acre) over that period.

HISTORY AND ECONOMIC EFFECTS OF EPIDEMICS

We now know that isolates of *Colletotrichum* have probably been disseminated worldwide through international plant exchanges (Smith, 2007) and that AFR, caused by *C. acutatum*, “has over the last 20 years developed from a localized, but serious disease of strawberry in hot humid areas of the southern United States to one that is worldwide in prominence” (Dale et al., 2007). We are also informed in B.J. Smith’s paper (Smith, 2007) that the greatest losses due to anthracnose on strawberry from AFR are caused by *C. acutatum*, and that anthracnose diseases of strawberry are second only to Botrytis in causing economic losses to strawberry growers in North America and

Table 1. U.S. strawberry-harvested area by primary growing system (annual strawberry plasticulture and matted row), and estimated nursery plant usage in 2003.^a

	Harvested hectares (acres)	Estimated plants/ha (plants/acre)	Total plant use (millions)
Strawberry plasticulture			
California	11,980 (29,600)	58,440 (23,650)	700.00 ^v
Florida	2,870 (7,100)	46,200 (18,700)	132.8
North Carolina ^x	809 (2,000)	37,060 (15,000)	30.0
Other states ^w	955 (2,360)	37,060 (15,000)	35.4
		<i>Subtotal</i>	898.2
Matted-row and other perennial systems			
Michigan	485 (1,200)	15,380 (6,224) ^y	7.5 (2.5) ^u
New York	607 (1,500)	15,380 (6,224) ^y	9.3 (3.1) ^u
Ohio	445 (1,100)	15,380 (6,224) ^y	6.8 (2.3) ^u
Oregon	1,052 (2,600)	30,754 (12,446) ^t	32.4 (10.8) ^u
Pennsylvania	526 (1,300)	15,380 (6,224) ^y	8.1 (2.7) ^u
Washington	688 (1,700)	30,754 (12,446) ^t	21.2 (7.0) ^u
Wisconsin	364 (900)	15,754 (6,224)	5.6 (1.9) ^u
		<i>Subtotal</i>	(30.3) ^u
		<i>Total annual use</i>	928.5

^aSource of 2003 statistics for the U.S. strawberry industry: National Agricultural Statistics Service and *Fruit and Tree Nuts Outlook*, FTS-317, Economic Research Service, USDA, 28 July 2005.

^bThe 700-million plant requirement for the California strawberry industry is based on information provided by Dan Legard during the 2005 Austin workshop; it is noteworthy that about two-thirds of the total plant supply is for short-day cultivars and one-third is for day-neutrals (cold-stored and fresh-dug). This calculation of the day-neutral plant requirement is derived from information in Sjulín (2007) which indicates that 65 million cold-stored day-neutral cultivars are produced by California nurseries for fruit plantings along the southern California coast (requiring about 65,000 plants/ha, or 26,300 plants per acre), and about 160 million fresh-dug plants of day-neutral cultivars are needed to annually supply the Watsonville/Salinas and Santa Maria districts, assuming an average of 50,000 plants/ha (20,235 plants per acre).

^cProduction area in North Carolina of 809 ha (2000 acres) in 2003 is derived from the survey conducted by S. Toth and B. Poling of annual strawberry plasticulture states participating in the Methyl Bromide Critical Use Application to the U.S. EPA (www.smallfruits.org).

^d“Other states” with strawberry plasticulture production in 2003 include VA (111 ha), TN (71 ha), SC (219 ha), GA (101 ha), AR (101 ha), AL (61 ha), OH (13 ha), NJ (81 ha), KY (1 ha), LA (162 ha), MD (12 ha), IL (13 ha), and MO (8 ha); data were derived from the survey conducted by S. Toth and B. Poling of annual strawberry plasticulture states participating in the Methyl Bromide Critical Use Application to the U.S. EPA (www.smallfruits.org).

^eEstimate of plant usage per ha for matted row in these states is based on a standard recommended spacing of 0.6 m × 1.06 m (2 ft × 3.5 ft).

^fAnnual planting needs in the matted-row states may be estimated by dividing the total production area by 3, as matted-row beds are commonly fruited for 3 yr (four production seasons).

^gEstimate of plant usage per ha for matted row in these states is based on a spacing of 0.3 m × 1.06 m (1 ft × 3.5 ft).

worldwide (Smith, 2007). Specific accounts of economic loss due to *C. acutatum* infection are given below, along with some additional reports by workers who did not participate directly in the workshop.

Florida. Barbara Smith was able to relate in her oral presentation (this information does not appear in her paper) that in recent years losses to AFR in Florida have averaged \$3 million USD per year; she also noted in 1997–1998 that losses due to fruit rot in Florida were estimated to be between \$10 and \$15 million USD. Assuming that AFR losses in Florida have averaged around \$3 million USD annually in recent years, this would represent $\approx 1.7\%$ of the value of the Florida crop in 2004 (\$178 million USD).

California. Anthracnose of strawberries in California, caused by *C. acutatum*, is more common in nursery areas (Strand, 1994), but it can be a serious problem in fruit-production areas if the pathogen is present and conditions are favorable. In his workshop presentation, “An effort to get the attention of researchers who work with *Colletotrichum acutatum*,” Curt Gaines identified four significant outbreaks of *C. acutatum* in California in recent years, including an AFR epidemic in 2002 that “Cost the fruit industry (CA) millions of dollars, and was due to contamination of all levels of plant production in 2002” (Gaines, 2005).

In his presentation, “Maintaining plant quality in strawberry propagation nurseries: a horticulturist’s perspective,” Kirk Larson identified a serious incident in Southern California in 2003 in which plugs became infected with *C. acutatum* during the misting and rooting phase of strawberry plug propagation (Poling and Parker, 1991), and large quantities of expensive plant material (plugs are about double the cost of fresh-dug or “tops-off” bare-root transplants) had to be destroyed.

North Carolina. In the same year (2003), this pathogen was highly destructive in plug plant propagation beds and greenhouses across the state of North Carolina, as well as in Virginia, South Carolina, and southern New Jersey. I am personally affiliated with a relatively small plasticulture industry in North Carolina (slightly in excess of 750 ha in 2003), by comparison with California (11,980 ha) and Florida (2870 ha), where *C. acutatum* was positively diagnosed in plug plants being grown from Canadian runner tips in Aug. and Sept. of 2003; as a result, an estimated 8 million plug plants had to be destroyed less than 1 week before planting for most of the affected growers.

Midwest and Northeast. By the early 1990s, epidemics of AFR began to occur in a number of matted-row strawberry-growing states the Northeast and Midwest (personal communications with Mike Ellis, Ohio State University, and Marvin Pritts, Cornell University). Ellis (not a workshop participant) has furnished this background statement:

“Actually in 1991, the disease did not only occur in Ohio, it was epidemic throughout the Northeast and Midwest from the Mississippi to

the Atlantic and from Wisconsin through the lower Midwest. It had never been seen before that time as far as I know, and I am positive that it was not considered as a problem that required control. One grower in Ohio had been growing berries for 40 years and had never seen the disease until 1991, when he lost 2 acres of (strawberry cv.) Lateglow berries to fruit rot. Eighty-eight percent of the fruit in the planting was infected.” (M. Ellis, personal communication)

Marvin Pritts, horticulturist and department chair, Cornell University, also confirmed epidemics of AFR in commercial strawberry fruit plantings in the Northeast, including New York and Pennsylvania (M. Pritts, personal communication). Because one workshop participant directly associated the growth in annual plasticulture production in the United States over the last 20 years with increased fruit losses to *Colletotrichum* spp. (Smith, 2007), it is instructive to note that *C. acutatum* losses have also occurred in matted-row plantings and with matted-row cultivars.

CULTIVAR SUSCEPTIBILITY

As previously noted, in the 1997–1998 winter season in Florida, AFR losses were estimated by Smith to be as high as \$10–15 million USD, and this comment served to trigger one of the more interesting discussions of the entire workshop which related to the importance of having anthracnose-resistant cultivars. Although there seems to be little question about the long-term importance of having disease-resistant cultivars, as was emphasized by most presenters, including Freeman, Sjulín, and Smith, there seemed to be considerable question about the short-term usefulness of current resistant cultivars, such as the 1992 University of Florida introduction, Sweet Charlie, which is resistant to AFR (Chandler and Legard, 2003).

Smith stated in her presentation that losses would have been much more severe in the 1997–1998 Florida strawberry season if 40% of the acreage had not been planted to ‘Sweet Charlie’. However, later in the workshop, Dan Legard, Director of Research and Education, California Strawberry Commission, Watsonville, CA (who had formerly worked in Florida as a plant pathologist), observed that winter plantings of ‘Sweet Charlie’ were sharply lower in the Florida 1998–1999 season, despite significant losses to AFR in susceptible cultivars from the previous year (\$10–15 million USD). Legard went on to say, “Growers don’t grow cultivars for disease resistance, they grow it for yield and marketability and other characteristics. And, so breeding for resistance is only usable if you actually have high productive cultivars with good marketable qualities.”

The shipping-quality issues with ‘Sweet Charlie’ are well documented, and in a more recent publication, *The Strawberry: A Book for Growers, Others*, Florida researchers acknowledge that “This cultivar in west

central Florida is currently in decline due to short “shelf-life” in warm weather (Chandler and Legard, 2003). In the year 2000, the University of Florida (UF) released the cultivar Strawberry Festival (Chandler, 2000); this cultivar is widely credited for the Florida industry’s healthy expansion in the early 2000s (Florida ranks second in U.S. strawberry production). By 2006, ‘Strawberry Festival’ occupied 60% of Florida’s ≈ 3035 ha (7500 acres) of annual hill plastic mulch production (N. Peres, invited speaker, Southeastern Strawberry Expo, Nov. 9, 2006, personal communication). However, ‘Strawberry Festival’ has resistance neither to *Colletotrichum* crown rot caused by *Colletotrichum gloeosporioides* nor to AFR (caused primarily by *C. acutatum*). Another important cultivar in Florida is Treasure, which was released in 2000 by a private breeding program (J&P Research, Naples, FL); this cultivar is well adapted to west central Florida and has resistance to *Colletotrichum* crown rot (Chandler and Legard, 2003). The majority of fresh-dug bare-root green transplants plants for the Florida market are produced in the Canadian Provinces of Nova Scotia, Ontario, Prince Edward Island, and Quebec, with lesser quantities coming from western North Carolina and northern California.

California. In the California industry, the main nonproprietary (public) short-day cultivar was Camarosa in 2003, which is susceptible to *C. acutatum* (Casado-Díaz et al., 2006). Ventana is a popular short-day cultivar that has been introduced in more recent years by the University of California, but Gubler (2005) has identified a more localized problem with this newer cultivar and its apparent AFR susceptibility:

“While the problem was assumed to be incited by C. acutatum, there were other factors that seemed to influence the severity of the disease, such as the cultivar and environmental factors. However, we do not know what exactly happened underlying the phenomenon. Varietal susceptibility and stresses should be studied in order to fully understand what might happen under certain situations (Gubler, 2005)”

Essentially, none of the public or private day-neutral cultivars propagated by California nurserymen is resistant to *Colletotrichum* spp. (Sjulín, 2007). Regarding day-neutral strawberry cultivars, which are now very important to the California strawberry industry, the principal problem is simply that “no day-neutral cultivars have been developed to date that combine *Colletotrichum* resistance with acceptable levels of horticultural traits” (Sjulín, 2007). About one-third of the California’s nursery production for California fruit growers in 2003 was in day-neutral cultivars, with the balance being made up of short-day types (see Table 1). California fruit production in 2004 (valued at \$1.22 billion USD) is based almost entirely on plant material produced by California nurseries, and workshop participant Dan Legard estimated that $\approx 700,000$ plants were produced for the state’s strawberry industry (all susceptible strawberry cultivars).

North Carolina. Susceptible short-day cultivars also predominate in North Carolina (809 ha), as well in other states in the mid-South, Mid-Atlantic, and the Midwest, which have adopted strawberry plasticulture in recent years (Table 1); the most popular cultivar is Chandler (Poling, 2003), which is very susceptible to *Colletotrichum* spp. The estimated plant usage on an annual basis is ≈30 million plants in North Carolina [≈18 million Chandler, susceptible (“s”) to *Colletotrichum* crown rot (caused by *C. gloeosporioides*) and AFR (caused by *C. acutatum*)], 10 million Camarosa (“s”), 1.5 million Sweet Charlie [resistant to AFR (caused by *C. acutatum*), “r_a”], and other cultivars including Bish (“r_a”), but these appear to be susceptible to crown rot caused by *C. gloeosporioides*. Thus, only ≈6–7% of the production area in North Carolina is planted in cultivars that are resistant to AFR caused by *C. acutatum*. The majority of plants for the North Carolina market, as well as for growers in other states in the mid-South, Mid-Atlantic, and in the Midwest who have adopted strawberry plasticulture, are produced in Canadian nurseries in Southern Ontario and Prince Edward Island as either runner tips (for plugs) or fresh-dug bare-root plants. Nursery plants are also produced in North Carolina under a certification program (NC Certified Plants), and those grown at higher elevations in western North Carolina are primarily fresh-dug bare-root plants raised for fruit growers in Florida (mainly ‘Strawberry Festival’ and ‘Treasure’).

HOW HAS THIS PATHOGEN BECOME SO WIDELY SPREAD OVER NORTH AMERICA?

It is not entirely well understood how *C. acutatum* has become North America’s dominant anthracnose pathogen in the span of about two decades, but soon after the turn of the new millennium, a major discovery was made by Leandro et al. (2001), namely, that *C. acutatum* can sporulate and germinate on symptomless strawberry leaves. This scientific finding not only helps us to appreciate the seriousness of the challenge confronting North America nurserymen in controlling an “invisible” pathogen in their nursery fields, but it may also offer the best explanation as to how *C. acutatum* has become so widespread over the North American continent since it was first diagnosed in the United States in the mid-1980s by workshop participant Barbara Smith.

Initial evidence of *C. acutatum* in the United States. Before this fungus was identified in North America, it had previously been reported in Queensland, Australia, in the mid-1960s (Smith, 2007). In Smith’s paper, “Epidemiology and Pathology of Strawberry Anthracnose,” she speculates that *C. acutatum* had probably been present in the United States for some time under the name *Gloeosporium* spp. (Maas, 1984). In a less widely circulated report that I came across after the workshop, I learned that *C. acutatum* was

also found in California strawberries in 1983, and the pathogen was noted to sporadically cause disease outbreaks typified by plant stunting, crown rot, and collapse, especially in early southern California plantings (Wilhelm, 2004).

1987 NASGA meeting. I can personally remember attending a North American Strawberry Growers (NASGA) Winter Conference in Feb. 1987 (Nashville, TN), soon after *C. acutatum* had been implicated in severe AFR problems in both the Southeastern United States and Southern California (Maas, 1987). At this meeting, USDA plant pathologist John Maas presented an overview of *Anthracnose Disease of Strawberry* in the United States and stated in the 1987 Proceedings of the NASGA Winter Conference, “More information is urgently needed on the reactions of (strawberry) cultivars to these fungi (*Colletotrichum fragariae*, *C. gloeosporioides*, and *C. acutatum*)” (Maas, 1987).

To his credit, John Maas was trying to get our attention about the potential seriousness of *C. acutatum* (Maas, 1987), 17 years before our *Anthracnose on Strawberry* workshop in Austin. We now know that all important nursery areas in the United States (north and south) and Canada are within the range of *C. acutatum* infection, but relatively little information was presented by participants in that program (on video tape or in the papers) that specifically addressed how extensively *C. acutatum* has infiltrated nursery production areas outside of California. The pathogen’s presence in California nursery plant growing areas is well documented (Strand et al., 1994).

Ideal nursery and host plant conditions. The Freeman and Sjulín papers help to underscore the most favorable kinds of environmental conditions for the spread of this pathogen through nursery plants. Relatively warm and wet weather conditions occurring during strawberry bloom and fruit ripening create what workshop participant Tom Sjulín describes as “an ideal situation for disastrous infection by *Colletotrichum* fungi, particularly *C. acutatum*” (Sjulín, 2007). And, as we learned in Austin, warm and wet environmental conditions can occur in California nursery production areas, making the management of day-neutral cultivars (which flower during the long days of summer) “much more problematic in the nursery than comparable short-day cultivars” (Sjulín, 2007).

Plant host susceptibility related to temperature. Workshop participant Stanley Freeman identifies in his paper (Freeman, 2007) that conducive temperatures for *C. acutatum* are in the range of 15–30 °C, and it is interesting that Legard noted in his presentation (Legard, 2005) that in California there have been benefits associated with delayed digging of nursery plants (when temperatures are cooler), compared with early-dug transplants for Southern California fruit producers that can sometimes have more serious problems with anthracnose root rot. Harvesting nursery plants under cooler temperature conditions, as is normally the case

in Canada when fresh-dug bare-root plants are dug for North Carolina growers (usually late September through October), may help explain why there have been so few occurrences of AFR in this type of transplant relative to plugs (Poling, 2005). In contrast, runner tips (used for plug propagation) are harvested ≈1 month earlier than fresh-dug bare-root plants, under temperature conditions that can still be very warm in the northern United States and Canada.

Spores are easily moved through the North American nursery system. Despite the very limited information available at this time describing the extent of this pathogen’s actual areas and path of spread in North America (outside of California), Dale et al. (2007) caution that, “There is now a considerable body of evidence to suggest that the spores are carried on strawberry plants moved by the nursery trade throughout, within and between countries.” This remark is no doubt referencing the discovery by Leandro et al. (2001) that *C. acutatum* can be carried on apparently healthy plants to other nurseries and nursery systems.

Another troubling implication of the research by Leandro. A second troubling dimension of the research by Leandro et al. (2001) was identified by Stanley Freeman, who sees the formation of secondary conidia on strawberry leaves without penetration as a “mechanism that enables the pathogen to survive and proliferate on the different host and non-host leaf surfaces” (Freeman, 2007). This brings into question our knowledge of the host range and specificity of *C. acutatum* obtained from strawberry plants (Freeman, 2007; Sjulín, 2007; Smith, 2007). It may also be important to rethink whether susceptible hosts are the only way this disease can be moved around, and there may be value in looking at nonplant surfaces as well.

In reference to the question about how the pathogen is gaining entrance to the plant production system, it is known that *C. acutatum* has a wide host range, but it is not clear whether it comes into the system from alternate hosts. Surveys are needed to determine if the pathogen occurs in the vicinity of nursery production. Sjulín (2007) reviews the more recent research of special concern to the California nursery industry regarding outbreaks of *C. acutatum* on almonds and highbush blueberry, but to date, he concludes that “isolates of *C. acutatum* commonly found on strawberry seem to be distinct from isolates on most other crops except cultivated anemone (*Anemone coronaria* L.), and there is little evidence of cross-infection except from anemone.”

In her paper, “Epidemiology and Pathology of Strawberry Anthracnose: A North American Perspective,” Barbara Smith tested the hypothesis that primary infection in strawberry (fruit) fields is sometimes assumed to come from other host crops (other fruit or vegetable hosts) growing near the strawberry field, but her findings did not suggest that primary anthracnose infections in strawberry fields are rarely from other

diseased fruit or vegetable hosts and are most often from infected strawberry transplants.

However, Freeman (2007) points out that *C. acutatum* from strawberry can survive on several cultivated plant species, such as pepper, eggplant, tomato, bean, and weed species, without causing disease symptoms, and he raises the possibility that alternate hosts can serve as a potential inoculum reservoir for strawberry infection between seasons. Further research in North American nursery production areas that have had a past history of *C. acutatum* outbreaks will better determine whether there is potential cross-infection issue with alternate hosts. Dale et al. (2007) reinforce the points made by Freeman (2007) and Sjulín (2007), that healthy nursery stock plants must be separated from field edges to avoid contamination from wild or weedy hosts.

These are not concerns of strictly academic interest, as a strawberry nursery grower who follows the strictest regimen of *preventative measures*, including 1) starting with clean plant material (Pesic-Van Esbroeck, 2005; Dale et al., 2007; Sjulín, 2007); 2) hot water treatment of dormant stock (Gaines, 2005; Larson, 2005; Sjulín, 2007); and 3) soil disinfections (Dale et al., 2007; Sjulín 2007), may still have questions, such as, “How much isolation (distance) is needed from previously infested fields with *C. acutatum* in my production area?” And, if the latter question cannot be answered satisfactorily, then, “How much chemical control should be used as a preventive measure?”

The strobilurans can be effective in strawberry anthracnose control, but extra care must be taken not to overuse these fungicides in the nursery for reasons related to loss of these materials down the line in fruit-production fields for reasons of resistance development.

MINIMIZING THE POTENTIAL OF SELLING *C. ACUTATUM*-INFECTED TRANSPLANTS

The control of this pathogen is clearly a high-priority issue for the California strawberry nursery industry, and California participants (Gaines, 2005; Larson, 2005; Legard; Sjulín, 2007) spent much of their time in Austin identifying nursery management practices and strategies to help nursery growers minimize the potential of selling *C. acutatum*-infected transplants to fruit growers.

Until the release of resistant cultivars, effective control of *C. acutatum* in nurseries will require an integrated approach that includes, as Sjulín states in his paper, “elimination of inoculum sources, reduction of host plant susceptibility, and either chemical or biological control” (Sjulín, 2007).

Hot water therapy is one of the main tools used in California nurseries to control anthracnose in planting stocks (Sjulín, 2007). A potential disadvantage to the approach mentioned by Freeman (2007), however, is its unknown long-term effects on plant development and yield.

Both Dale (2007) and Pesic-VanEsbroeck (2005) identify micropropagation as a preferred tool for ridding strawberry plants of *Colletotrichum* sp. infections in the initial stock plants that are used at the beginning of the strawberry propagation cycle (in contrast to hot water therapy). Dale (2007) provides an extensive discussion of the protocols used to test for viruses, mycoplasmas, bacteria and various fungi (including *Colletotrichum* sp.) in plantlets produced from micropropagation.

California workshop participant C. Gaines emphasized a series of “integrated” steps nursery managers can employ to minimize the potential *C. acutatum* infections throughout the nursery propagation cycle. Table 2 represents the author’s attempt to summarize the various management strategies used by California nursery growers to eliminate/reduce pathogen inoculum, and the information in this table may be of practical benefit to nursery growers in Canada and the northern United States, where *C. acutatum* infestations have also occurred. One of the added challenges faced by eastern nurseries is related to their “humid” climate by contrast to the generally arid summer climate in California nursery areas (Gaines, 2005).

Gaines (2005) and Larson (2005) noted the critical importance of removing “free

water” in the nursery production field by using drip irrigation instead of overhead sprinklers. Freeman (2007) further described strawberry cultivation techniques used in Israel that take advantage of plastic covers over the crop to significantly control anthracnose disease incidence by reducing inoculum spread and infection in both nurseries and fruit-production fields.

BETTER TOOLS NEEDED FOR NURSERY SAMPLING AND DETECTION

The *urgent* need for better methods of nursery field sampling and detection of *C. acutatum* in asymptomatic plants with latent infections of this pathogen was spelled out in a very memorable Austin workshop presentation by Curt Gaines, former nursery grower but now strawberry industry liaison with the Office of Technology Transfer (OTT), University of California. Nursery growers require reliable diagnostics to guide their disease-control practices, and it was the contention of Gaines that being able to rapidly and economically diagnose *C. acutatum* in symptomless plant material at each step in the multiyear nursery plant propagation cycle (foundation, registered, and certified

Table 2. Suggested nursery production practices to help reduce, if not eliminate, strawberry anthracnose infection and spread in nursery plants in California and other important nursery regions in North America.

A. Nursery field	
1. Ideal scenario ^a would be to have a field with no past history of <i>Colletotrichum</i> spp. infestations	
a. <i>C. acutatum</i>	
b. <i>C. gloeosporioides</i>	
c. <i>C. fragariae</i>	
2. Complete isolation from any host plant (strawberry) commercial fruit production	
3. Adequate separation from strawberry nursery plants with day-neutral characteristics	
4. Separation from potential alternate host plants (various weeds, trees, shrubs, vegetables, and fruit crops)	
5. Broadcast soil treatment with efficacious fumigant at full rates before each production cycle	
6. Nursery field rotation cycle; ideally 3 yr	
7. Climatic conditions	
a. Daytime temperatures below the optimum range for <i>Colletotrichum</i> spp.	
b. Seasonal rainfall distribution	
i. Arid summer conditions are preferred	
ii. In areas prone to periodic summer rains, it is best to have cooler daytime temperatures	
B. Proven practices for the elimination of primary inoculum	
1. Enforced policy against using new cultivars, or breeding lines, that have not gone through “clean-up”	
2. Use of tissue-culture explants from Foundation Plant Services in California ^b	
3. Hot water therapy for planting stock (Sjulín, 2007)	
C. Proven practices for preventing spread of inoculum	
1. Irrigation delivery—drip irrigation (no overhead sprinkler irrigation)	
2. Irrigation water—not re-cycled	
3. Protectant sprays to prevent colonization using strobilurin class of fungicides (pyraclostrobin and azoxystrobin)	
4. Equipment and worker sanitation	
D. Practices to reduce host plant susceptibility; see <i>Proceedings</i> papers by Sjulín (2007) and Smith (2007)	
1. Frequent removal of blossom clusters	
2. Reduce standing water in the field	
3. Limit nitrogen applications late in the growing season	
4. Avoid ammonium forms of nitrogen	

^aThe author is not aware of any nursery, or nursery region in North America, that fits all the criteria specified under an “ideal field nursery” scenario; however, several examples of nursery areas do meet the first criterion of not having any past history of anthracnose infestation, and these include an isolated strawberry nursery on Prince Edward Island, Canada, and a relatively new high-elevation nursery in the Rocky Mountains of the United States.

^bSee Dale et al. (2007) for information on the use of micropropagation as an effective tool to rid strawberry plants of *Colletotrichum* spp. infections.

plants) would greatly assist nursery growers (and plant inspectors) in minimizing the potential of selling *C. acutatum*-infected transplants to fruit growers. Gaines felt so strongly about this message that, several minutes before the start of the workshop began, he handed me another computer diskette with the same PowerPoint talk, but a different title. He had changed the title from "An integrated approach to managing *Colletotrichum acutatum* through the use of meristem plants, nursery isolation and sanitation measures" to "An effort to get the attention of researchers who work with *Colletotrichum acutatum*" (ASHS Workshop Video: *Anthrachnose on Strawberry: Management Strategies for Plant and Runner Tip Nurseries*, CD # 2).

We learned in Austin from Dan Legard that the California Strawberry Commission would soon be undertaking the funding of new research projects to 1) determine how important pathogens are introduced and spread in California nurseries and 2) develop the tools and methods to detect *C. acutatum* to prevent the introduction and spread of this pathogen in the nursery.

FINAL REFLECTIONS

Hopefully, the video and written proceedings of this workshop will motivate other scientists, industry members, and representatives from different North American strawberry systems to engage in a more meaningful future dialogue on questions related to the overall health of the North American strawberry plant supply.

Unfortunately, we now know that isolates of *Colletotrichum* have probably been disseminated worldwide through international plant exchanges (Smith, 2007) and that AFR, caused by *C. acutatum*, has become widely spread over the North American continent since it was first diagnosed in the United States in the mid-1980s by workshop participant Barbara Smith. Sadly, we cannot turn back the clock by two decades and impose a North American quarantine on *C. acutatum*, as the Europeans have done (Bosshard, 1997; Casado-Diaz et al., 2006).

The fact that this pathogen has so many new addresses in the United States and Canada today is an important indication that the overall "nursery system" in North America is in need of substantial improvement. Dale et al. (2007) conclude their paper with an appeal for a better North American nursery system process to address *Colletotrichum* infections and to inevitably bring about "common standards of health and sanitation." They note that eradication of *Colletotrichum* infections will "depend on considerable cooperation and openness between the different nursery systems in North America" (Dale et al., 2007).

Nursery system representatives could benefit from exchanging information, as we did in Austin, on current research to propagate strawberry nursery stock plants free of *C. acutatum* infection and to identify reliable

methods of keeping "specific pathogen-tested plants" (Dale, 2007) free of *Colletotrichum* spp. beyond the screenhouse stage in the nursery propagation cycle (field phase), which is where "most infections of nursery stock occur" (Dale, 2007). We did not have adequate time in Austin to discuss how future cooperation between different nursery, research, extension, and certification systems in North America might actually work, but this may be an opportune time for representatives of these groups to meet and identify collective measures that can be taken to minimize the potential of selling transplants that are latently infected with *C. acutatum* to fruit growers.

Regulatory programs for certification of plant materials have been historically slow to change (Nelson-Kluk, 2006), but as new technology for the detection of *C. acutatum* in asymptomatic nursery plants becomes available (hopefully, in the very near future), it would seem appropriate to convene members of the North American nursery system not only to discuss utilization of these diagnostic tools but also to take up issues related to appropriate field-sampling strategies for *C. acutatum* (Legard, 2005). Some of the leading publicly supported services that make up the North American Strawberry Nursery System include the University of California's Foundation Plant Services, The North Carolina Micropropagation Center (and NC Certified Plant Growers), and Canadian services such as the one explained by Dale et al. (2007) herein. Organizations directly involved in issues related to "common standards of health and sanitation" (Dale et al., 2007) include various state Departments of Agriculture in the United States and their provincial counterparts in Canada (Ministries of Agriculture), who are responsible for plant protection, certification, and regulatory matters.

It is very challenging to breed strawberry cultivars that combine resistance to *Colletotrichum* spp. and good horticultural characteristics and market acceptance. Part of the problem may relate to a high level of diversity in the pathogen population (Legard et al., 2003), but when an intensive seedling screening is applied for crown rot resistance, and seedling populations are segregated for fruit rot resistance, it is possible to achieve resistant strawberry cultivars, such as Pelican, which is resistant to both fruit and crown rot (Smith et al., 1998). Planting resistant cultivars such as Carmine and Sweet Charlie has consistently controlled AFR in Florida (Mertely and Peres, 2005), but when moderately susceptible cultivars (e.g., Strawberry Festival) or highly susceptible cultivars (e.g., Camarosa and Treasure) are grown, regular applications of fungicides are often needed to suppress the AFR (Mertely and Peres, 2005). And although strobiluron fungicides have been especially effective in controlling anthracnose infection in susceptible strawberry cultivars, there is the risk at some point in the future of resistance developing to this class of fungicides.

Now, breeding strawberry cultivars that combine resistance to *Colletotrichum* spp. with acceptable levels of horticultural traits may seem cost-prohibitive compared with other methods of control. However, if the North American strawberry industry would take into consideration the full economic cost of hot water therapies, strobiluron plant dips, the expense of various fungicide applications that are now used to control AFR in both commercial nursery and fruit production, as well as the long-term viability of control strategies that depend on routine pesticide applications (for susceptible and highly susceptible strawberry cultivars), then a greater investment in breeding for anthracnose resistant short-day and day-neutral cultivars could prove to be a win-win proposition on both economical and environmental bases.

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