Progress Report 2014 for SCRI Project #: 2010-51181-21140

Integrated management of zoosporic pathogens and irrigation water quality for a sustainable green industry

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Non-Technical Summary

This SREP project addresses three SCRI focus areas and aims to improve and maintain the health of nursery and floral crops from the time of production to delivery to the consumer, to protect water quality and to increase water use efficiency by the green industry. The ultimate goals are to move horticultural production and distribution towards greater sustainability and enable nurseries and greenhouses to better compete in global markets. Supporting objectives are to (1) characterize zoosporic pathogens found in irrigation systems and assess their potential impact on ornamental crop health; (2) understand water quality dynamics, develop guidelines to assist irrigation managers in improving crop quality and productivity, and assess the environmental benefits of increased water recycling practices; (3) significantly increase the understanding of the aquatic biology of Phytophthora and Pythium species and develop protocols for risk assessment and mitigation of these pathogens in irrigation systems; (4) identify and enhance naturally-occurring pathogen-suppressing microbes in reservoirs; (5) assess the changes in production costs and revenue enhancements when the resultant knowledge and technologies are implemented as best management practices (BMPs); and (6) develop and use an online knowledge center to deliver information and education programs and facilitate BMP implementation. This project will increase the profitability and sustainability of the green industry, enhance the aesthetic value of recreational parks and landscapes, and improve consumer satisfaction with the plants they purchase. It will reduce the risk of dissemination of quarantine pathogens (e.g., Phytophthora ramorum) through trade of ornamental plant stocks. These benefits will extend to other specialty crop producers facing similar crop health and water issues.

Major Goals of the Project

This project addresses two critical issues facing the nation's $17 billion green industry (www.nass.usda.gov) through the integration of systems-based, interdisciplinary research and extension activities. It seeks to boost adoption of water recycling irrigation systems, build sustainable plant health beginning during production and extending to garden centers and to the ultimate consumer, and to increase consumer confidence in the quality of plants they purchase. Our ultimate goals are to move the green industry towards greater sustainability and enable nurseries and greenhouses to better compete in global markets while protecting the environment and meeting consumer demands for high quality, healthy plants. The specific objectives are: 1. Characterize species and taxa of *Phytophthora* and *Pythium* found in irrigation systems and assess their potential risk to the health of ornamental crops. 2. Develop a better understanding of the dynamics of water quality parameters in reservoirs and develop guidelines to assist irrigation managers in mitigating the risk of nutrient deficiency and toxicity. 3. Significantly increase the understanding of the biology of zoosporic plant pathogens and apply the knowledge to develop best management practice (BMP) protocols for mitigating the dissemination of plant pathogens through irrigation systems. 4. Identify and enhance the buildup of naturally-occurring beneficial microbes in irrigation reservoirs that inhibit zoosporic pathogens. 5. Integrate the BMPs for waterborne pathogen suppression and improved irrigation water quality into current crop systems. 6. Evaluate the effects that the adoption of BMPs have on production costs, revenue enhancement, and associated social and environmental benefits. 7. Develop an online knowledge center on waterborne pathogens and irrigation water quality management, and use the website to deliver information and educational programs to growers, students and other scientists in order to quickly disseminate science-based knowledge and encourage the adoption of the BMPs developed through this project. This project will generate a wealth of new knowledge and several novel technologies that will have immediate and long-term impacts on the green industry.

What was accomplished under these goals?

Research data translation and dissemination to end users has emerged as a central theme of our project activities this past year. The most significant accomplishments included: (i) a well-attended 14-session webinar series on irrigation pathogens and water quality, and (ii) publication of a comprehensive reference resource on irrigation pathogens.

The webinar series was added to the project for an expedited dissemination of resultant knowledge and technology and for the broadest reach to end users possible. Each session was advertised nationally via AmericanHort and the Society of American Florists as well as other local and national networks of growers, diagnosticians and extension professionals. The webinar series was launched in October of 2013 and delivered monthly via Adobe Connect at https://connect.extension.iastate.edu/irrigation-water/. Several sessions were conducted in collaboration with leading growers in water decontamination technologies. The webinar series has attracted attendance from coast to coast and from Canada to Florida. All sessions were archived at http://www.irrigation-pathogens.ppws.vt.edu/webinar/index.php for future viewing.

The reference book project was undertaken to maximize the reach and impact of this project by raising the awareness of the growing global water shortage and associated pathogen recycling risk. The content was developed in order to educate specialists and larger growers, and to encourage young scientists to enter this field of research. As indicated in the book title, this reference resource summarizes the current knowledge about the biology, detection and management of plant pathogens in irrigation water. This book, published by the American

Phytopathological Society, includes five sections: (i) linkage between crop disease and irrigation water, (ii) diversity and biology of plant pathogens in irrigation water, (iii) detection technology and economic threshold for plant pathogens in irrigation water, (iv) pathogen management through water treatment, and (v) pathogen management through effective system design and best practices. This book was a result of an international collaboration involving 49 leading agricultural engineers, horticulturists, irrigation specialists, microbiologists and plant pathologists from three continents (Africa, America, and Europe). It is regarded as "an ideal textbook and highly recommended for Agricultural Department curriculums and Academic Library reference collections." (http://www.apsnet.org/apsstore/shopapspress/Pages/44266.aspx).

In addition, we continued research to further develop our understanding of water quality dynamics, pathogen aquatic biology, and economics of water recycling. To date, a total of nine new species and one new taxon of *Phytophthora* have been characterized and described from nursery irrigation systems in Virginia and Mississippi. Among them, *P. stricta* represents a new clade in the genus while majority of the other news species form a high temperature cluster within clade 9. None of these new species and taxon has caused severe disease or damage to ornamental crops at local nurseries, nor have they survived well in soilless potting mixes. These results, however, do not necessarily mean that they pose no or low risk to crops under different conditions and/or elsewhere. These studies have already facilitated worldwide identification of the above species and diseases they cause as indicated by *P. hydropathica*. They also have raised some fundamental questions regarding the origin, ecological function and horticultural implications of these novel species while challenging the current phylogeny of the genus *Phytophthora*.

Continuous monitoring at two commercial greenhouses in Pennsylvania has demonstrated that irrigation water holding tanks harbor numerous *Pythium* species, especially those characterized by filamentous, non-inflated sporangia (Group F of Plaats-Niterink). In addition, one greenhouse harbors *Pythium helicoides*, *P. middletonii*, *P. rostratifigens* and two species that are new to science. The second greenhouse harbors *Pythium chamaehyphon* and one species that is new to science. Resultant cultures were tested to determine their cardinal temperatures of growth and sensitivity to a widely used fungicide, mefenoxam. Analyses of DNA sequences on these isolates were intensified in order to determine identity and to characterize new species. In greenhouse experiments where these isolates were used to inoculate geraniums each separately and in combination with the highly pathogenic *Pythium aphanidermatum*, *P. irregulare*, and *P. cryptoirregulare*, there did not appear to be disease inhibitory or enhancement effects between *Pythium* species.

Analyses of water quality and weather data collected from multiple locations in Virginia and Maryland over the past 4 years have identified for the first time that thermal stratification occurs in shallow recycling irrigation reservoirs. These data revealed water quality variations at different depths of the water column and along water path within reservoirs from the entrance to the outflow point. These new findings document the dramatic diurnal and seasonal fluctuations of water quality in these reservoirs and have direct applications in irrigation pathogen and water quality management.

In addition to water pH and electrical conductivity, dissolved oxygen (DO) was determined to be a major factor limiting zoospore survival in recycling irrigation reservoirs. Zoospores survived the best at a DO level of 5 to 6 mg/L, equivalent to that of tap water. Zoospore survival

decreased with DO reduction down to 0 mg/L or elevation up to 20 mg/L and above in lab assays simulating its fluctuation ranges documented for recycling irrigation reservoirs.

In-depth analyses of grower survey data regarding irrigation and disease management practices and attitudes toward recycling irrigation and rainfall runoff have resulted in a number of new findings with policy implications. First, among the 198 respondent growers were 50 adopters and 148 non-adopters. The adopters would recycle in response to at least one of the two choice questions while the non-adopters would not recycle in response to both questions. Compared to non-adopters, adopters had a lower proportion of respondents from retail and a higher proportion from container, field nursery, and hoop house production. Adopters and non-adopters were similar in terms of years of experience. Compared to non-adopters, adopters were less likely to be the owners of their businesses, more likely to be a head grower, and more likely to have a four-year college degree. Adopters had higher total firm costs and nursery costs compared to non-adopters. Second, cost and disease are deterrents to recycling while water scarcity is not a consideration for the decision to recycle. Growers would need to be compensated 7% their nursery production cost to accept the risk of increased disease associated with recycling. Wide spread adoption of water recycling technologies is unlikely to occur in the Mid-Atlantic region without regulation. Financial assistance (tax credits, cost share, subsidies, loans) could encourage growers to invest in infrastructure to capture and recycle water. Research and outreach can demonstrate ways to recycle without increased disease risk, thereby increasing grower acceptance of recycling.

Additionally, the project team effectively addressed the immediate need for recommendations concerning the containment of boxwood blight, an emerging disease, through collaborations with regulatory personnel and extension ornamental pathologists. These collaborations have produced six best management practices (BMPs) protocols each targeting a specific clientele group. These BMPs provide the most up-to-date information regarding boxwood blight management and are available at http://www.ext.vt.edu/topics/agriculture/commercial-horticulture/boxwood-blight/index.html.

What opportunities for training and professional development has the project provided?

Eight graduate research assistantships: Cao, Dart, D'Alessio, Ferraro, Lanze, Ree, Yang, Xu

Four postdoctoral research fellowships: Avenot, Burgos-Garay, Nikrad, Zhang

These graduate students and postdoctoral fellows were sent to workshops for professional development while learning required skills for performing their parts of the project. They also were sent to professional meetings to present their research data and network with peers. For example, Mrina Nikrad attended the Mothur Workshop in Detroit, MI (March 2014), Carla E. Lanze participated in the Ooomycete Bioinformatics Workshop at Virginia Tech in Blacksburg, VA (June 2014) and Xiao Yang participated in two workshops (Analysis of Population Genetic Data in R *and* Introduction to Bayesian Analysis in Plant Pathology) in Minneapolis, MN (August 2014). Herve Avenot, Norm Dart, and Xiao Yang attended the 2nd International Boxwood Summit in Beltsville, MD (May 2014). Carla E. Lanze and Xiao Yang presented their results at the Annual Meeting of American Phytopathological Society in Minneapolis, MI (August 2014). Xiao Yang also participated and presented his research and moderated a session at the 19th Ornamental Workshop on Diseases and Insects in Hendersonville, NC (September 2014). Haibo Zhang participated in the AWRA Annual Water Resources Conference in Tysons

Corner, VA (November 2014). All graduate students and postdoctoral fellows were mentored as they prepared data for publication.

Fourteen webinar sessions: irrigation pathogens and water quality, for the industry and other stakeholders

How have the results been disseminated to communities of interest?

Webinar series: Irrigation Pathogens and Water Quality

A 14-session webinar series was advertised throughout the U. S. and delivered via Adobe Connect at https://connect.extension.iastate.edu/irrigation-water/. It was well attended and participants included growers, extension agents and specialists and other stakeholders from coast to coast and from Canada to Florida. All webinar sessions including discussion were recorded and archived at http://www.irrigation-pathogens.ppws.vt.edu/webinar/index.php.

1. Project Team. 2013. A path to plant biosecurity, water and environmental sustainability – SCRI Project overview. Held on October 8, 2013 and recording posted at https://connect.extension.iastate.edu/p8c8irvmphw/
2. Pease, J. 2013. Disease management and irrigation practices of Mid-Atlantic ornamental nurseries. Held on November 6, 2013 and recording posted at https://connect.extension.iastate.edu/p7vxio4amkj/
3. Moorman, G. W. 2014. What plant pathogens could be in irrigation water? Held on December 3, 2013 and recording posted at https://connect.extension.iastate.edu/p3u8rvp77kf/
4. Moorman, G. W. 2014. How do plant pathogens get into and move in irrigation water? Held on January 7, 2014 and recording posted https://connect.extension.iastate.edu/p5k9xrwl0vb/
5. Moorman, G. W. 2014. How do we determine irrigation water is clean or contaminated? Held on February 4, 2014 and recording posted at https://connect.extension.iastate.edu/p6g6f7h6dj2/
6. Hong, C. X. 2014. Chlorination of recycled water in ornamental horticultural production. Held on March 4, 2014 and recording posted at https://connect.extension.iastate.edu/p56g9fijkmi/)
7. Copes, W. E. 2014. Alternative disinfectant treatments. Held on April 8, 2014 and recording posted at https://connect.extension.iastate.edu/p1pbnh37awv/
8. Ristvey, A. 2014. Substrate management practices vital for pathogen risk mitigation. Held on May 6, 2014 and recording posted at https://connect.extension.iastate.edu/p8a3yfye8s2/
9. Lea-Cox, J. D. 2014. Pathogen recycling risk mitigation through system design and best management practices. Held on June 3, 2014 and recording posted https://connect.extension.iastate.edu/p514ujen4de/
10. Hong, C. X. 2014. Locating a new production facility for crop health and sustainability. Held on July 1, 2014 and recording posted at https://connect.extension.iastate.edu/p7uv8isuow4/
11. Hong, C. X. 2014. Building pathogen risk mitigation into water recycling systems. Held on August 5, 2014 and recording posted at https://connect.extension.iastate.edu/p7j64j891gy/

12. Hong, C. X. 2014. Recycled water quality dynamics and implications for crop health and production. Held on September 2, 2014 and recording posted at https://connect.extension.iastate.edu/p7csfg98et9/
13. Hong, C. X. 2014. Water pH management for improved horticultural productivity and profit margin. Held on October 7, 2014 and recording posted at https://connect.extension.iastate.edu/p1ec2ajsn5v/
14. Hartter, D., Boyle, K., Pease, J., Bosch, D., D'Alessio. 2014. Understanding consumer preferences for ornamental plants with disease-free and water conservation labels. Held on November 4, 2014 and recording posted at https://connect.extension.iastate.edu/p4wiyfsyslr/

Newsletter articles

1. Hong, C. X. 2014. Three reasons to irrigate plants in the early to mid-morning. Virginia Nursery and Landscape Association (VNLA) Newsletter 84(1):66-68
2. Hong, C. X. 2013. Water pH dictates chlorine performance. VNLA Newsletter 83 (4):58-60

Related extension publications

1. Avenot, H., Baudoin, A., Bordas, A., Bush, E., Dart, N., Hansen, M. A., Hong, C. X., Likins, T. M., Martin, D, and Nichols, L. 2014. Virginia boxwood blight task force. Virginia Cooperative Extension Publication No.: PPWS-30NP at http://pubs.ext.vt.edu/PPWS/PPWS-30/PPWS-30.html
2. Bush, A., Hansen, M. A., Dart, N., Hong, C. X., Bordas, A., and Likins, T. M. 2014. Best management practices for boxwood blight in the Virginia home landscape. Virginia Cooperative Extension Publication No.: PPWS-29NP at http://pubs.ext.vt.edu/PPWS/PPWS-29/PPWS-29.html
3. Dart, N., Hong, C. X., Bordas, A., Bush, A., Hansen, M. A., and Likins, T. M. 2014. Best management practices for boxwood blight in Virginia production nurseries WITHOUT boxwood blight. Virginia Cooperative Extension Publication No.: PPWS-33NP at http://pubs.ext.vt.edu/PPWS/PPWS-33/PPWS-33.html
4. Dart, N., Hong, C. X., Bordas, A., Bush, A., Hansen, M. A., and Likins, T. M. 2014. Best management practices for boxwood blight in Virginia retail nurseries WITH boxwood blight. Virginia Cooperative Extension Publication No.: PPWS-34NP at http://pubs.ext.vt.edu/PPWS/PPWS-34/PPWS-34.html
5. Dart, N., Hong, C. X., Bordas, A., Bush, A., Hansen, M. A., and Likins, T. M. 2014. Best management practices for boxwood blight in Virginia retail nurseries WITHOUT boxwood blight. Virginia Cooperative Extension Publication No.: PPWS-35NP at http://pubs.ext.vt.edu/PPWS/PPWS-35/PPWS-35.html
6. Hansen, M. A., Bush, A., Bordas, A., Dart, N., Hong, C. X., and Likins, T. M. 2014. Best Management Practices for Boxwood Blight for Greenery Producers. Virginia Cooperative Extension Publication No.: PPWS-39NP at http://pubs.ext.vt.edu/PPWS/PPWS-39/PPWS-39-pdf.pdf

Related extension presentations

Hong, C. X. 2014. Boxwood blight: avoidance and control. "Kick-off the Season" Specialist Day, Painter, VA, March 11, 2014

Presentations to the External Reviewers of Virginia Tech's Hampton Roads AREC

1. Kong, P., Richardson, P. A., Yang, X, Zhang, H. B., Ghimire, S. R., Copes, W. E., Moorman, G. W., Lea-cox, J. D., and Hong, C. X. 2014. Biology of *Phytophthora* species in aquatic ecosystems
2. Zhang, H. B., Richardson, P. A., Belayeh, B. E., Ristvey, A., Lea-Cox, J. D., Copes, W. E., Moorman, G. W., and Hong, C. X. Recycling irrigation reservoirs: thermal stratification and water quality variation

One-on-one consultations with growers

Numerous consultation were conducted through on-site visit, email exchange and via phone conversation to advise on irrigation pathogens and irrigation water quality. Disease diagnoses were completed on samples submitted by growers, retailers, landscapers as well as extension agents concerned about plant pathogens in irrigation water.

What do you plan to do during the next reporting period to accomplish the goals?

In addition to the activities outlined in the proposal for the final year of this project, we will endeavor to explore some new research horizons of fundamental importance to the national and global plant biosecurity. Specifically, we will:

1. Construct a new phylogeny for the genus *Phytophthora* by integrating the new clades and recently described species as a result of this project. This work will be foundational for developing and implementing sustainable risk mitigation plan for pathogens in irrigation systems and beyond at national and global scales.
2. Expand the hunt in runoff containment basins for naturally occurring biological control agents. This work has begun with investigations into the diversity of algae in recycling irrigation reservoirs and their interactions with selected *Phytophthora* species.
3. Explore the differences in the genetic makeup between aquatic and terrestrial species of *Phytophthora* and *Pythium* and their association with genes regulating pathogenicity.
4. Model the seasonal and diurnal water quality fluctuations in runoff containment basins. This research integrates the initial four years of environmental and water quality data for better understanding the water quality dynamics. It aims to provide a tool for water quality manipulation in order to suppress pathogens, improve crop productivity and quality as well as a tool for assessing water resource conservation and protection benefits of capturing and recycling runoff water.
5. Develop a better understanding of the interactions between the isolates of *Pythium* very frequently found in recirculating irrigation water but not associated with crop losses and those species of *Pythium* that are known to cause significant crop losses in commercial greenhouses. This research is being conducted by a graduate student as part of her Master of Science degree research project at Penn State University.
6. Morphological and physiological characteristics of species of Pythium (known and new-to-science species) will be determined. Their plant pathogenicity on geranium seedlings and cardinal temperatures in culture will be determined. Two students, Carla Lanze and Laura del Sol Bautista-Jalon, will participate at the Oomycete Molecular Genetics Network meeting and the Fungal Genetics Conference (Asilomar Conference Center in Pacific Grove, CA) in 2015. These students will receive two weeks of training in genotyping-by-sequencing analysis at Cornell University's Institute of Biotechnology.

Both will apply this training to the analysis of Pythium isolate DNA, submit manuscipts to scientific journals, and present research results at the August 2015 American Phytopatholgical Society meeting in Pasadena, CA. Carla Lanze will complete her M. S. degree requirements. BMPs for *Pythium* management in greenhouses will be completed and added to the Knowledge Center. A risk assessment guide for use by Knowledge Center visitors will be completed and made available.

7. Conduct case studies of growers in Virginia, Maryland, and Pennsylvania to estimate costs of recycling.
8. Estimate relationship between premiums consumers are willing to pay for plants grown using water conserving methods and growers' costs of implementing such methods.

Participants – Actual FTE for this Reporting Period

Target Audience

Nursery growers and greenhouse producers
Garden centers, retailers, and landscapers
Agricultural industry scientists and consultants
Extension specialists and agents
Plant disease diagnosticians, regulatory personnel
Undergraduate and graduate students, postdoctoral associates
Educators, horticulturists, mycologists, and researchers
Conservation biologists
Government policy makers

Products

Publications

Book

1. Hong, C. X., Moorman, G. W., Wohanka, W., and Büttner, C. (eds). 2014. Biology, Detection and Management of Plant Pathogens in Irrigation Water. APS Press, St. Paul, MN, USA

Book chapters

1. Büttner, C., Hong, C. X., Moorman, G. W., and Wohanka, W. 2014. Preface. *In* Biology, Detection and Management of Plant Pathogens in Irrigation Water. C. X. Hong, G. W. Moorman, W. Wohanka, and C. Büttner (eds.). American Phytopathological Society, St Paul, MN, USA
2. Copes, W. E., Barbeau, B. and Chastagner, G. A. 2014. Chlorine dioxide for irrigation water treatment. Pages 251-266 *In* Biology, Detection and Management of Plant Pathology in Irrigation Water. C. X. Hong, G. W. Moorman, W. Wohanka, and C. Büttner (eds.). American Phytopathological Society. St. Paul, MN, USA
3. Elmer, W. H., Buck, J., Ahonsi, M. O., and Copes, W. E. 2014. Emerging technologies for irrigation water treatment. Pages 289-302 *In* Biology, Detection and Management of Plant Pathology in Irrigation Water. C. X. Hong, G. W. Moorman, W. Wohanka, and C. Büttner (eds.). American Phytopathological Society. St. Paul, MN, USA
4. Hao, W., Vinatzer, B. A., and Hong, C. X. 2014. Pasteurization for irrigation water treatment. Pages 187-195 *In* Biology, Detection and Management of Plant Pathogens in

Irrigation Water. C. X. Hong, G. W. Moorman, W. Wohanka, and C. Büttner (eds.). APS Press, St Paul, MN, USA

5. Hong, C. X. 2014. Management of plant pathogens in irrigation water. Pages 74-75 *In* Compendium of Rhododendron and Azalea Diseases. R. Linderman and D. M. Benson (eds.). American Phytopathological Society, St. Paul. MN, USA
6. Hong, C. X. 2014. Developing a facility and production plan for management of plant pathogens in irrigation water. Page 75 *In* Compendium of Rhododendron and Azalea Diseases. R. Linderman and D. M. Benson (eds.). American Phytopathological Society, St. Paul. MN, USA
7. Hong, C. X. 2014. Selecting a water treatment technology for control of plant pathogens in irrigation water. Pages 75-76 *In* Compendium of Rhododendron and Azalea Diseases. R. Linderman and D. M. Benson (eds.). American Phytopathological Society, St. Paul. MN, USA
8. Hong, C. X. 2014. Component analysis of irrigation water in plant disease epidemiology. Pages 111-121 *In* Biology, Detection and Management of Plant Pathogens in Irrigation Water, C. X. Hong, G. W. Moorman, W. Wohanka, and C. Büttner (eds.). American Phytopathological Society, St Paul, MN, USA
9. Hong, C. X. 2014. Economic threshold of plant pathogen in irrigation water. Pages 175-183 *In* Biology, Detection and Management of Plant Pathogens in Irrigation Water, C. X. Hong, G. W. Moorman, W. Wohanka, and C. Büttner (eds.). American Phytopathological Society, St Paul, MN, USA
10. Hong, C. X., Büttner, C., Moorman, G. W., and Wohanka, W. 2014. A partial list of plant pathogens found in water to date. Pages 389-411 *In* Biology, Detection and Management of Plant Pathogens in Irrigation Water, C. X. Hong, G. W. Moorman, W. Wohanka, and C. Büttner (eds.), American Phytopathological Society, St Paul, MN, USA
11. Ivors, K. L. and G. W. Moorman. 2014. Oomycete Plant Pathogens in Irrigation Water. Pages 57-64 *In* Biology, Detection, and Management of Plant Pathogens in Irrigation Water. C. X. Hong, G. W. Moorman, W. Wohanka, and C. Büttner (eds.). American Phytopathological Society, St. Paul, MN, USA
12. Kong, P., and Lea-Cox, J. D. 2014. Water quality dynamics and influences on pathogen mitigation in irrigation reservoirs. Pages 333-346 *In* Biology, Detection and Management of Plant Pathology in Irrigation Water. C. X. Hong, G. W. Moorman, W. Wohanka, and C. Büttner (eds.). American Phytopathological Society, St. Paul, MN, USA
13. Lea-Cox, J. D., and Ross, D. S. 2014. Water management to minimize pathogen movement in containerized production systems. Pages 377-388 *In* Biology, Detection and Management of Plant Pathology in Irrigation Water. C. X. Hong, G. W. Moorman, W. Wohanka, and C. Büttner (eds.). American Phytopathological Society, St. Paul, MN, USA
14. Moorman, G. W., A. J. Gevens, L. L. Granke, M. K. Hausbeck, K. Hendricks, P. D. Roberts, and T. R. Pettitt. 2014. Sources and Distribution Systems of Irrigation Water and Their Potential Risks for Crop Health. Pages 3-11 *In* Biology, Detection, and Management of Plant Pathogens in Irrigation Water. C. X. Hong, G. W. Moorman, W. Wohanka, and C. Büttner (eds.). American Phytopathological Society, St. Paul, MN, USA

15. Moorman, G. W. 2014. Irrigation Water and the Health of Greenhouse Crops. Pages 23-29 *In*: Biology, Detection, and Management of Plant Pathogens in Irrigation Water. C. X. Hong, G. W. Moorman, W. Wohanka, and C. Büttner (eds.). American Phytopathological Society, St. Paul, MN, USA
16. Ristvey, A. G. and G. W. Moorman. 2014. An Integrated Approach to Minimizing Plant Pathogens in Runoff Water from Containerized Production Systems. Pages 365-375 *In* Biology, Detection, and Management of Plant Pathogens in Irrigation Water. C. X. Hong, G. W. Moorman, W. Wohanka, and C. Büttner (eds.). American Phytopathological Society, St. Paul, MN, USA
17. Ross, D. S. 2014. Water resources and designs of recycling irrigation system for healthy crops. Pages 321-332 *In* Biology, Detection and Management of Plant Pathology in Irrigation Water. C. X. Hong, G. W. Moorman, W. Wohanka, and C. Büttner (eds.). American Phytopathological Society, St. Paul, MN, USA

Refereed journal articles

1. Burgos, M., Hong, C. X., and Moorman, G. W. 2014. Complex heterotrophic bacterial interactions with plant pathogenic *Pythium* in recycled irrigation water. HortScience 49:961-967.
2. Dart, N., Hong, C. X., and Bradley, W. T. 2014. An improved leaf disc bioassay for detecting microsclerotia of *Calonectria pseudonaviculata* in soil and potting media. Plant Disease
3. Hao, W., and Hong, C. X. 2014. Heat treatment induced bacterial changes in irrigation water and their implications for plant disease management. World Journal of Microbiology and Biotechnology 30:1591-1601 (online version at doi: 10.1007/s11274-013-1583-y)
4. Kong, P., and Hong, C. X. 2014. Oxygen stress reduces zoospore survival of *Phytophthora* species in a simulated aquatic system. BMC Microbiology http://www.biomedcentral.com/1471-2180/14/124
5. Yang, X., Copes, W. E., and Hong, C. X. 2014. Two novel species representing a new clade and cluster of *Phytophthora* species. Fungal Biology 118:72-82
6. Yang, X., Gallegly, M. E., and Hong, C. X. 2014. A new high-temperature tolerant species in the clade 9 of the genus *Phytophthora*: *P. hydrogena* sp. nov. Mycologia 106:57-65 (online version at doi:10.3852/13-043)
7. Yang, X., and Hong, C. X. 2013. *Phytophthora virginiana* sp. nov., a high-temperature tolerant species from irrigation water in Virginia. Mycotaxon 126:167-176 (online version at http://dx.doi.org/10.5248/126.167)
8. Yang, X., and Hong, C. X. 2014. *Halophytophthora fluviatilis* sp. nov. from freshwater in Virginia. FEMS Microbiology Letters 352:230-237 (online version at doi: 10.1111/1574- 6968.12391)
9. Yang, X., Richardson, P. A., and Hong, C. X. 2014. *Phytophthora×stagnum* nothosp. nov., a new hybrid from irrigation reservoirs at ornamental plant nurseries in Virginia. PLoS One at http://dx.plos.org/10.1371/journal.pone.0103450
10. Copes, W., Yang, X., and Hong, C. X. 2014. *Phytophthora* species recovered from irrigation reservoirs in Mississippi and Alabama nurseries and pathogenicity of three new species. Plant Disease (submitted)
11. Zhang, H. B., Richardson, P. A., Belayeh, B. E., Ristvey, A., Lea-Cox, J. D., Copes, W. E., Moorman, G. W., and Hong, C. X. 2014. Recycling irrigation reservoirs: thermal

stratification and its implications for crop health and production. Irrigation Science (submitted)

12. Zhang, H. B., Richardson, P. A., Belayeh, B. E., Ristvey, A., Lea-Cox, J. D., Copes, W. E., Moorman, G. W., and Hong, C. X. 2014. Characterization of water quality in stratified recycling irrigation reservoirs. Agricultural Water Management (Submitted)

Abstracts

1. Douglas, S. M., Benson, D. M., Crouch, J. A., Dart, N., Daughtrey, M., Hong, C. X., Ivors, K. L., LaMondia, J. A., Marra, R. E., Palmer, C. L., and Shishkoff, N. 2014. Boxwood blight and the dawn of a research collaboration. Phytopathology 104:S3.147
2. Lanze, C., and Moorman, G. W. 2014. Characterization of *Pythium* spp. frequently found in recycled irrigation water. Phytopathology 104:S3.66
3. Yang, X., Tyler, B. M., and Hong, C. X. 2014. Constructing a new phylogeny for the genus *Phytophthora*. Phytopathology 104:S3.133

Invited lecture and presentations

1. Kong, P., and Hong, C. X. 2014. Effects of water quality on survival of zoosporic oomycetes and implications. Annual Meeting of American Society of Horticultural Science, Orlando, FL, July 27 to August 1, 2014
2. Kong, P., Richardson, P. A., Yang, X, Zhang, H. B., Ghimire, S. R., Copes, W. E., Moorman, G. W., Lea-cox, J. D., and Hong, C. X. 2014. Biology of *Phytophthora* species in aquatic ecosystems. The 7th IUFRO Working Party 7.02.09 on *Phytophthora* in Forests and Natural Ecosystems. Esquel, Chubut, Argentina, November 10 to 14, 2014
3. Yang, X., Cope, W. E., and Hong, C. X. 2014. *Phytophthora* species found in irrigation systems and their risk assessments. The 19th Ornamental Workshop on Diseases and Insects, Hendersonville, NC, September 29 to October 3, 2014
4. Yang, X., Tyler, B. M., and Hong, C. X. 2014. A multi-locus phylogeny for the genus *Phytophthora*. The 7th IUFRO Working Party 7.02.09 on Phytophthora in Forests and Natural Ecosystems. Esquel, Chubut, Patagonia Argentina, November 10 to 14, 2014

Other Products

Physical collections

1. Numerous isolates of *Pythium* from the continuous baiting of recycling irrigations systems in two commercial greenhouses in Pennsylvania were accumulated and some are part of a working collection of over 100 isolates from this research. DNA from each isolate was extracted and is stored at -20C as part of this collection in the Moorman Lab at the Pennsylvania State University.
2. Many isolates of *Phytophthora*, including the type cultures of ten new species and taxon, were recovered from one commercial nursery in Mississippi. The type cultures of these new species along with over 2000 bacterial strains from pond surveys in Virginia are part of a working collection maintained in the Hong Lab at Virginia Tech. More than 1000 DNA sequences of *Phytophthora* species and bacteria have been deposited at the Genbank for public access.