Finding the Gaps: An Assessment of Concepts, Skills, and Employer Expectations for Plant Pathology Foundational Courses

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Plant pathology is a multidisciplinary science, spanning scales from molecular, through organismal and field practices, up to global-scale modeling. The field encompasses a diverse array of individual subject areas, including agriculture, horticulture, soil science, microbiology, mycology, virology, plant physiology, molecular biology, biochemistry, genetics, epidemiology, and statistical modeling. Our academic faculty and programs reflect this diversity and bring a broad range of perspectives and approaches to plant pathology education.

Just as the field of plant pathology is broad and integrative, so are our students. Our introductory plant pathology courses serve students in numerous degree programs, both in and out of plant pathology. Most undergraduates who take an introductory course in plant pathology are not plant pathology majors, and only four U.S. universities even offer a bachelor's degree in plant pathology, though several others have tracks or specializations that emphasize plant pathology. At the University of Florida, which offers no undergraduate plant pathology degree but does offer a specialization in plant health within the plant sciences major, the introductory plant pathology laboratory course served 199 undergraduate students from 19 different declared majors over a six year period (2011 to 2016), of which only seven students (3.5%) were pursuing a degree in plant science on the plant health specialization track. At the University of Wisconsin – Madison, which does offer a bachelor's degree in plant pathology, the introductory plant pathology course served

393 undergraduate students from 31 different majors over the same six years. Only 10.9% of those students were plant pathology majors. The majority of students in introductory plant pathology courses at both of these institutions are majoring in plant-related disciplines. These plant-focused students often rely upon a single introductory plant pathology course to provide them with the tools they need to recognize and appropriately triage plant disease problems in their own fields of work.

As the field of plant pathology has expanded to incorporate new interdisciplinary approaches and a rapidly proliferating array of research methods, it has become more challenging for faculty and administrators to design appropriate introductory courses and undergraduate-level curricula to meet the needs of this diverse student population. The perceived conflict between teaching fundamental concepts and applied research skills adds another layer of complexity. The added challenge of balancing the core knowledge and vocabulary of the field with realistic research experiences has become a common topic in educator meetings within the field of plant pathology. For example, within the American Phytopathological Society Teaching Committee, there has been a perennial dialog over the past decade around the function of introductory courses, asking (i) how much emphasis should we be placing on core knowledge versus on research skills? and (ii) what objectives are most important for our introductory courses, versus objectives that are better emphasized elsewhere in the curriculum?

Beyond the individual course decisions made by teaching faculty, administrative reorganizations and changing emphases in research and faculty hiring are likely to impact the content of introductory plant pathology courses, but there has been no explicit attempt to examine this question. The number of standalone plant pathology departments has decreased by more than 50% since the mid-1970s, as budget reductions have reduced faculty hiring in multiple plant science-related fields, and the smaller departments have been merged into multidisciplinary units (Martyn 2009). Following a recent trend of departmental mergers, there are currently fewer than 30 universities in the U.S. that have specified plant pathology departments (i.e., where “plant pathology” is part of the

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department name), and introductory plant pathology courses are housed in many departments, including plant science, agricultural sciences, biology, forestry, and microbiology. The infraposition of plant pathology within these various academic foci may influence introductory course content, as the perspectives and interests represented by each department determine the educational priorities and available resources for teaching plant pathology. Over the past few decades, research emphasis in plant pathology, as in many plant science-related fields, has also shifted from applied to basic research, with increasing specialization particularly in molecular biology (Martyn 2009). A 2007 census of land grant universities found that only 73% of faculty in plant pathology departments held their PhD degrees in plant pathology (Gadoury et al. 2009). Furthermore, they found evidence that faculty who came from other disciplines did not view plant pathology as their primary professional association, despite being housed in plant pathology departments: membership in the American Phytopathological Society was only 81% across all faculty, but 90% among those whose PhD degrees were in plant pathology. In a study by MacDonald et al. (2009), over 50% of plant pathology program heads expressed significant concern ('fairly concerned' [3] or 'highly concerned' [4] on a 4-point rating scale) that their department may not be able to maintain adequate coverage in the traditional areas of plant pathology; 60% of these program leaders already cited lack of faculty in the traditional areas as having a negative impact on their recruiting abilities. No one has yet examined whether or how this shift in faculty specialization and disciplinary identity is reflected in introductory courses. Those departments with less plant pathology identity (interdisciplinary departments and/or departments with high ratios of faculty from other disciplines) may differ in their expectations and emphases with regards to introductory coursework, relative to those with stronger disciplinary identity and more traditional programs, and introductory courses at these institutions may be more likely to be taught by faculty whose own background and research interests lie elsewhere. These potential differences may be appropriate within their programs, but they may also create gaps in fundamental knowledge and skills among students whose only formal education in plant pathology is through the introductory course offered at their undergraduate institution. There is currently no data to determine the extent to which these differences do in fact exist, and if they do, how they impact students' preparedness for the work force.

In addition to changes in administrative units and faculty specializations, the increasing use of distance education delivery systems is likely to be a factor influencing the specific skill sets that students will gain from their introductory plant pathology coursework (Bruce et al. 2005; D'Arcy et al. 2009; Schumann 2003). As in other disciplines, the use of distance education platforms is increasing among plant pathology departments (Curtis 2002; Schumann 2003), and several introductory courses around the country are currently offered online. Historically, introductory courses have typically included laboratory exercises to give students basic skills in handling samples, recognizing diseases, and isolating and identifying pathogens. Though it may appear a straightforward task to convert pedagogical pieces such as lectures and written exercises to distance formats, effective distance learning cannot be achieved by simply recording lectures, but requires specific strategies tailored to the distance learning environment (e.g., Sugar et al. 2007; Zheng and Smaldino 2003). Laboratory components in turn present even more challenges for conversion, especially given the special equipment and supplies required for students to practice lab skills, and the resource demands associated with guiding the practice-based exercises at multiple locations or through individual instruction. Departments have variously addressed these challenges by offering non-lab distance courses, reducing the authentic practice-based components to exercises that students can do on their own, or requiring distance students to participate in condensed live laboratory sessions. The strengths and weaknesses of each instructional delivery method can be expected to significantly impact the skills that students can learn in these courses.

The combination of individual faculty decisions and institutional influences results in a variety of approaches to teaching introductory plant pathology courses. Whereas most academic faculty likely have clear expectations as to what should be covered in an introductory chemistry or physics course, the content and skills covered in introductory plant pathology courses may vary widely, depending on the type of institution (research, land grant, liberal arts, etc.), the focus of the department (plant pathology versus other disciplines), the delivery method (laboratory versus lecture only, live versus distance), and the instructor's background (PhD discipline, current research interests). This variability has led to some fundamental questions among those responsible for developing plant pathology curricula and courses, and for those who evaluate instructors and courses in plant pathology:

- What are the core, "indispensable" concepts and skills that should be taught in an introductory plant pathology course?
- What do the "end users" (employers and/or instructors of higher-level courses) expect of students who have completed an introductory plant pathology course?
- How does course content vary across institutions, and how well does current content align with end user expectations?
- How has the expansion of distance education impacted the inclusion of hands-on skills, such as microbial culture techniques and disease identification, in introductory courses?

Faculty and administrators have lacked any real data upon which to evaluate and develop plant pathology course content at the undergraduate level. As in other STEM disciplines, employers in industry, government agencies, and other academic institutions have also had limited opportunity to provide input, and may hold unfounded expectations of graduates' preparedness for many plant pathology-related work functions (Carnevale et al. 2011). Although a great deal of recent educational research has focused on STEM education and the preparation of future STEM employees, little of this work has been done specifically within agricultural STEM disciplines, and less still in the plant sciences. Researchers at the Georgetown University Center on Education and the Workforce have conducted comprehensive analyses of STEM competencies and employment opportunities, and have called for efforts to better align teaching with workforce needs (Carnevale et al. 2011). Many researchers have suggested possible approaches to accomplish these improvements, including adding research components to classes (Weaver et al. 2008), incorporating inquiry-based learning (Siebert and McIntosh 2001), and analyzing employment listing criteria for alignment with curricula and instructor expectations (Sivakumar 2014). While the results of these studies naturally extend to plant pathology, there has been no effort as yet to specifically examine either employer expectations or current content and methods within this subject area.

The current body of knowledge on plant pathology instruction is bifurcated into two well-addressed scales of investigation: lesson plans and graduate student preparation. The literature is rich in examples of specific programs and lesson plans developed for use in outreach, predominantly at the high school level, and published almost entirely as abstracts in conference proceedings (e.g., Bernert et al. 2014; Daniels et al. 2013; Partridge and Osborne 1999; Santamaria et al. 2014). Through the American Phytopathological Society (APS) Education Center (<http://www.apsnet.org/edcenter/Pages/default.aspx>) and publications in various education-focused journals (e.g., *Journal of College Science Teaching*, *National Association of Biology Teachers*), instructors have some access to novel lessons and teaching methodology. These are excellent references for instructors in search of specific teaching tools and ideas for conveying various plant pathology concepts. The literature also provides good coverage of plant pathology education at the graduate curriculum level. In 2007, MacDonald et al. (2009) conducted an extensive survey-based study to examine the state of plant pathology education from three foci: student recruitment into the field, department heads' assessments of their programs' ability to meet self-defined key educational needs, and employers' desired skills for plant pathologists. This study provided a comprehensive

overview for plant pathology at the graduate program level, including administrator perceptions of critical courses, graduate students' perceptions of the positive and negative aspects of their education, and the attributes and skills desired by employers in academic, government, and private sectors. However, this work focused entirely on graduate-level education of plant pathologists, and employers' expectations of professional plant pathologists with MS or PhD degrees. There is scant research focused in between high school and graduate school, at the level of undergraduate courses and plant pathology education for students majoring in related fields, who may or may not continue on to graduate education in a plant pathology degree program.

We undertook this research to address the above questions in order to provide faculty and administrators with the tools they need to evaluate and update their courses, and to better align curriculum with the needs of employers in plant science related agencies and industries. The objectives of this research project were to:

- (i) Determine which concepts and skills are commonly taught in introductory courses throughout the U.S., and distinguish those content and delivery practices that are more likely to vary by department identity (plant pathology versus other programmatic foci);
- (ii) Assess the extent to which instructors are offering hands-on training in their introductory courses, and the formats through which they deliver that experience (e.g., laboratory sections, in-class demonstrations, self-guided assignments);
- (iii) Determine the extent to which introductory plant pathology courses are available through distance education, the format of those courses (e.g., fully online or mixed with in-person instruction), and what impact the transition to distance formats has had on incorporation of practice-based learning components;
- (iv) Determine what key concepts and skills are expected of students who have completed an introductory plant pathology course among managers in the private and public sectors, and how those employer expectations may differ from instructor content and emphasis;
- (v) Assess faculty perceptions of quality in introductory plant pathology courses (i.e., what components are required or advantageous to make a high-quality introductory course) and perceived barriers to achieving desired levels of quality;
- (vi) Invite employer feedback and suggestions for improving employment readiness of baccalaureate graduates.

With this work, we have begun to elucidate the variability in general plant pathology courses and the alignment of their content with workforce expectations on a national level. By surveying faculty, we have examined what they cover, how they present their content, and what constraints or demands influence the inclusion or exclusion of specific course components. By surveying employers in a variety of plant science-related fields, we have examined what employers expect from these courses, particularly for graduates who are entering the workforce with little or no additional coursework in plant pathology. The knowledge gained through the research presented here will support course and curriculum decisions for a critical subject that supports food, agricultural, and natural resource degree programs.

Methods

Survey methods. Two surveys were developed for this work: one for instructors, and the other for employers. The instructor survey targeted instructors of introductory undergraduate courses in plant pathology at postsecondary institutions within the U.S. and its territories. The employer survey targeted individuals who were responsible for hiring and/or managing entry-level employees in plant science-related fields, where entry-level was defined as employees holding a BA, BS, or Associate degree, with less than three years of full time experience.

Survey questions were developed by the paper authors, with input from members of the APS Teaching and Industry committees. The instructor survey included approximately 20 demographic and

background questions and 30 questions per course on the format, content, and skills covered. Questions included a mix of Likert-type scale responses, yes/no questions, and short-answer responses. The first three authors, instructors of introductory plant pathology courses themselves, generated the initial list of content, lab skills, and soft skills for the surveys based on their own syllabi, content of available plant pathology textbooks, and notes from previous APS Teaching Committee discussions. The fourth author added especially to the list of soft skills based on science education research, and the question lists were distributed to APS Teaching Committee members for additional edits and question contributions.

The employer survey included approximately 35 questions on employer background, type of organization, job functions of entry-level employees, and Likert-type responses as to the importance of content and skills expected of entry-level plant pathology employees – the same content and skills to which the instructors responded, but also including further questions about desired soft skills and experiences. These additional questions were designed to address employer expectations that would be more likely met on a curriculum level than within the individual courses described in the instructor survey. We also offered employers open-ended questions for them to describe perceived gaps in entry-level applicants' backgrounds as well as their suggestions for addressing the gaps. The final section for employers included questions about the support for employee professional development offered by their organizations. Both complete questionnaires are available for review as e-Xtra supplements to this article.

Face survey validation was conducted with pilot groups of four members each, with the instructor survey group containing members from both land grant and liberal arts institutions, and the employer survey group containing members from both private and government institutions. Each validation group member completed the survey and provided the authors written feedback on the survey, including overall length and organization, and clarity, relevance, and applicability of the individual questions. The first and fourth author revised the surveys accordingly. Both surveys were approved through the University of Florida Institutional Review Board (IRB# IRB201500962), and delivered online, using the Qualtrics platform (Qualtrics, Provo, UT).

Participants for the instructor survey were recruited primarily via e-mail invitations sent in 2016 from APS and partnering societies (National Association of Biology Teachers, NABT, and North American Colleges and Teachers of Agriculture, NACTA) through internal membership lists. At APS, invitations were sent directly to every member who had been identified by the teaching committee as an instructor, or who indicated an educational role in their member profiles. Additional participants were recruited via flyers during the 2016 annual APS meeting. A total of 110 participants initiated the survey, of whom 69 met the filter criteria and 65 elected to continue through the survey; the filter criteria were that the instructor was currently listed as the instructor or co-instructor for an undergraduate level course in general/introductory plant pathology, and that the course frequency was at least every other year. Sixty-five instructors from 41 different colleges and 35 different states and territories completed the instructor survey. Most of these instructors reported that they teach at public (93.8%) doctorate-granting (72.3%) universities. Only about half of the instructors (47.7%) were teaching in plant pathology departments, but 75.4% of respondents who had a research appointment reported plant pathology as their main area of research. All instructors held at least a master's degree; 90.6% held a doctoral degree. Most instructors (79.7%) held at least one degree in plant pathology or plant protection, with 70.3% of respondents holding a doctorate in plant pathology. Most instructors (98.5%) had taken plant pathology coursework in their own degree programs, with only one respondent reporting no formal training in plant pathology. Additional instructor demographic information is available as an e-Xtra supplement to this manuscript.

The instructor survey was designed to allow one instructor to provide information about more than one introductory course, in the event that a single faculty member taught multiple introductory

courses (for example, a nonmajors course and a majors course). Participants indicated that they taught one (78%), two (19%), three (1.5%), or four (1.5%) introductory/general courses, for a total of 80 unique courses. Of the 79 courses for which instructors described the course level, 27.8% were identified as being at a fundamental level (requiring no prerequisites), 53.2% at an intermediate level (intended primarily for life science majors), and 19% at an advanced level (for plant pathology majors and graduate students); 73.4% were required for at least one major at the college.

Participants in the employer survey were recruited through a combination of e-mail invitations and open announcements. APS staff delivered e-mail invitations through the general membership rosters, and invitations were also sent out through emails and e-newsletters to memberships of the National Association of Plant Breeders, the IR4 Project, Plant Management Network, AmericanHort, and the Botanical Society of America. A total of 117 employers completed the demographics portion of the survey, of whom 83 were recruited through APS and 34 were recruited by partner distributors; 90 participants completed the entire survey. Together, these 90 participants at the time they were surveyed managed a total of 965 BS-degreed entry-level employees. Participant distribution was representative across employment sectors, with 35.0% identifying their sector as private industry, 40.2% as academia (including extension), 17.1% as government research, 4.3% as government regulatory, 6.0% as nonprofit, and 5.1% as "other." The most common job functions included in participant work units were research, diagnostics, product development, plant production/maintenance, and regulatory compliance. Despite efforts to recruit participants from a range of plant science fields through professional organizations outside of APS, survey participants were skewed heavily toward plant pathology specializations, with 71.8% listing plant pathology among their specializations and 42.7% listing plant disease diagnostics. However, many other specializations were also well represented, including general botany/plant biology (34.0%), plant breeding (30.1%), mycology (29.1%), plant propagation and/or plant production/horticulture (22.3%), and microbiology (22.3%).

Analysis methods. Using IBM SPSS Statistics 24, the fourth author prepared descriptive statistics on the instructors' backgrounds, institutions, courses, and valuation of course components (Objectives i-iii, v). For this analysis, any instructor who reported teaching more than one course matching our specifications was only counted once, so for hypothetical instructor participant 37 who taught three courses, data for instructor background was only counted once. For courses, instructors indicating more than one course matching our descriptions were counted as individual courses; therefore, instructor participant 37 who taught three courses was separated into courses 37a, 37b, and 37c for course content analysis. The fourth author also calculated descriptive statistics for basic teaching methods, textbook choices, and course delivery for instructors, and used *t* test analysis to determine whether importance of content and skills varied based on department name (Objective i). The first author used χ^2 analysis with Fisher's exact test in JMP Pro 12 (SAS) to

examine the effects of department name on the number of introductory courses taught and the inclusion of a laboratory component in introductory courses (Objective i).

The fourth author also prepared descriptive statistics using SPSS 24 on the employers' backgrounds and institutions, and the functions of employees supervised, and the first author used ordinal logistic regression and Wilcoxon nonparametric analyses in JMP Pro 12 to determine whether skills desired by employers varied by employment sector (Objective iv).

For comparisons between employer expectations and instructor coverage of content and skills (Objective iv), the fourth author converted data from a 5-point scale used for employer responses to the 3-point scale asked of instructors for two question sets that asked each participant group about the same content and skills. Employers ranked content knowledge and skills expected of an entry-level applicant from 1 - no knowledge expected, to 5 - comprehensive knowledge expected (any answers to a sixth option, "I am not familiar with this subject area," were excluded). Instructors ranked content and skills as "1 - Not covered," "2 - Minimal coverage," or "3 - Covered as a learning objective," output as 1, 2, or 3, respectively. Therefore, we converted an employer response of 1 to match an instructor response of 1, employer 2 and 3 to match instructor "Minimal Coverage," and employer 4 and 5 to match instructor "Covered as a learning objective." Finally, comparisons of the importance of content and skills to each participant group were assessed using unpaired 2-tailed *t* tests in SPSS.

Instructors and employers were asked about soft skills in different ways, reflecting differences in the target audiences' scopes and objectives: instructors with a semester time scale and a focus on plant pathology instruction, versus employers with a potential time scale spanning years and a focus on job functions. This allowed only limited direct comparisons between soft skill survey questions. To compare the two skills asked about most similarly, literature search and critical reading, answers from the employer survey on a 5-point scale were again mapped to a 3-point scale matching the instructor responses. For the instructors, the numbering was reversed from previous questions, so a low number from instructors corresponded to higher numbers (4, 5) from employers (Table 1).

For the open-ended questions to employers about perceived applicant deficiencies, the first author categorized the responses by theme. Responses were first broken down into individual components, with each unique noted deficiency separated into its own data cell. Once separated, the listed items were coded by type of skill, knowledge, or attribute addressed. Many of the perceived deficiencies fell into groups identified in our survey: content knowledge, disciplinary skills, and soft skills, but additional themes, such as specific skill sets and personal attributes, emerged as the responses were sorted.

Educational terminology. Terminology around teaching and learning is constantly evolving. Next Generation Science Standards terminology is currently using "practices" to encompass ideas previously described alternatively as "hands-on," "inquiry-based," or

Table 1. Mapping of employer 5-point responses to instructor 3-point responses for content and laboratory skills importance

Content knowledge questions			Skills questions		
Employer original response (5-point scale)	Instructor response (3 levels)	Employer converted response	Employer original response (5-point scale)	Instructor response (3 levels)	Employer converted response
1 – No knowledge expected	Not covered (1)	1	1 – Not important to work unit	In course (1)	2
2	-	2	2	-	3
3	Minimal coverage (2)	2	3	Not in course (2)	3
4	-	3	4	-	1
5 – Comprehensive knowledge expected	Covered as learning objective (3)	3	5 – Critically important to work unit	Not in course, but elsewhere in curriculum (3)	1

“skills” (NGSS Lead States 2013). Practices are embedded in the context of appropriate content and may involve hands-on activities, or may involve reading and discourse as inquiry processes. In both the surveys and this manuscript, the authors have attempted to strike a balance between the most current terminology and common, colloquial terms more likely to be used by those outside of the field of education. Thus, we have used “hands-on” to represent any educational method in which students are actively manipulating samples, regardless of whether the protocols are instructor-proscribed or student-developed. We have used “inquiry” to describe hands-on or engaged discourse activities in which students are required to apply knowledge and contribute to the development of the activity. We have used “skills” to describe specific learned techniques, and “soft skills” to describe competencies that are not discipline specific (e.g., written communication, time management).

Survey Results

We present the results of our surveys here in four parts: instructor responses, employer responses, comparisons of instructor and employer responses, and open-ended employer responses about deficiencies in current applicants and suggestions for remedying the deficiencies. For the instructor responses, we present first how they teach, addressing questions about online versus in-person delivery and the extent of hands-on instructional opportunities, and then what specific content and skills they teach. For employers, we present expected content knowledge for entry-level employees, and then what laboratory and additional skills they desire in these employees.

Course delivery and materials: How are we teaching plant pathology? Most of the instructors reported courses taught in-person, with 33.3% of courses entirely in-person and 51.3% of courses in-person but with some online components. About 10% of the courses from the survey were reported to be offered fully online (6.4%) or blended (3.8%). A blended course format has a significant online component but also in-person meetings. For the remaining 6.4% of courses, students could choose to take the course either in an in-person format or an online format. Of the 13 online/blended courses, nine were adapted from a previous in-person format course, and five had a self-guided lab or field component. Instructors of online courses with a lab reported that the lab component consisted of online activities and simulations, hands-on field trips or demonstrations that students must visit in-person, or a combination of online and in-person activities. When asked “What components changed in the process of changing formats?” instructors had a variety of responses. These included: changing the format of their lectures to video recordings or text modules, changing the format of quizzes and exams to open book with more emphasis on synthesis, changing assignment formats to be submitted online, adding videos on various topics to enhance the online content, adding online quizzes, and adding a disease diagnosis video game. In one case, an instructor commented that student discussion was something that was lost in moving online while another instructor commented on the addition of student discussions in an online format. The changes reported here are consistent with common and best practices for creating online courses (Boettcher and Conrad 2010).

Traditional lectures were the primary mode of content delivery, with instructors reporting frequent use of lectures in 93.2% of courses (Table 2). More than half of instructors engaged students with frequent use of live sample materials and Socratic questioning. Other broadly used student engagement techniques (at least minimal use, by at least 50% of instructors) were: in-class discussions, project-based learning, inquiry-based learning, field trips, individual research projects, in-class problem sets, and out-of-class group assignments. Fewer than half of instructors reported using “flipped” lectures, graded lab notebooks, or student involvement in original research. When combining the student-originated and professor-driven research categories, 46% of instructors indicated that they involve students in research, with 28.4% reporting use of one type and 17.6% reporting use of both types. Additional active learning techniques listed (write-in responses) included analysis of case studies, short in-class written assignments, portfolio building, interviewing

professionals, debate, think-pair-share, disease collections, vocabulary word puzzles, clicker response quizzes, online interactive practice modules, and online video conferencing. Teaching techniques that instructors indicated were unfamiliar to them included Socratic questioning (unfamiliar to 10.8%), flipped lectures (9.5%), citizen science (9.5%), game-based learning (5.4%), and inquiry-based learning (4.1%).

Course content: What concepts and skills are essential to plant pathology courses? There was notable consistency in the content of the respondents’ courses. Of the 30 topic areas provided by the survey, 27 topics were taught at some level in more than 80% of courses (82.7 to 98.7% of the courses, Fig. 1). These topics were: disease cycles, environmental impacts on disease, fungal structures, fungal biology, fungal diseases, bacterial diseases, viral diseases, nematode diseases, cultural control, history of plant pathology, Koch’s postulates, principles of biotechnology, pathogenicity, resistance, gene for gene theory, plant defense, epidemiology, abiotic diseases, fungal taxonomy, bacterial structures, bacterial biology, viral structures, virus biology, nematode anatomy, nematode biology, pesticides, and biological control.

However, whether these topics were taught at a minimal level or as an important learning objective varied by topic. For example, disease cycles were taught in 97.4% of courses and considered an important learning objective in 85.5% of courses, while biotechnology was taught in 85.3% of courses but only considered an important learning objective in 25.3% of courses. Only three topics were taught somewhat less often and with more minimal coverage: bacterial, viral, and nematode taxonomy were taught in about 70% of courses (69.9 to 71.2%) and were important learning objectives in only 11 to 15.1% of courses. Other topics reported by the instructors in write-in responses were: pathogens in native ecosystems, invasive pathogens, new trends in plant pathology, breeding for resistance, evolution, bacterial symbioses, fungal symbioses, parasitic plants, integrated pest management, social impacts, human activities that contribute to disease risk, and sustainability.

The most common soft skill performed in class was writing, with 80.8% of courses including some kind of graded writing assignment. Giving a presentation, providing peer review, ability to do a literature search, and analysis of primary literature were targeted skills in about half of courses (45.8 to 58.3%). Only 64.0% of courses reported group work as a soft skill used in class. Other skills reported in write-in responses were experimental design, data analysis, and data reporting.

Table 2. Content delivery modes used in undergraduate plant pathology courses. Use of each technique was rated for a total of 74 courses. Nonresponses for a given method were counted as “no use” for that method. Percentages are rounded to a single decimal place; some rows do not total 100.0, due to rounding.

Technique	No use	Minimal use	Frequent use
Traditional lectures	1.4	5.4	93.2
Examination of live sample material	14.9	13.5	71.6
Socratic questioning	17.6	31.1	51.4
Project-based learning	18.9	33.8	47.3
In-class discussion (whole class)	17.6	36.5	45.9
Inquiry-based learning	25.7	28.4	45.9
Graded laboratory notebooks	54.1	4.1	41.9
Individual research writing assignments	43.2	21.6	35.1
In-class small group discussions	36.5	36.5	27.0
Out-of-class group assignments	50.0	23.0	27.0
In-class problem sets	47.3	27.0	25.7
Field trip(s)	36.5	41.9	21.6
Student-originated research projects	58.1	24.3	17.6
“Flipped” lectures	54.1	31.1	14.9
Game-based learning	64.9	29.7	5.4
Involvement in original research (professor-driven)	78.4	17.6	4.1
Participation in citizen science	87.8	8.1	4.1

Many of the courses (82.1%) had a lab component that was required (71.8%), or that was optional or required for only some majors (10.3%). Respondents answered questions about skills taught in their labs for 60 of the 74 courses that were identified as including a lab credit. Most, but not all, lab courses (81.7 to 88.3%) provided at least some training in sight recognition of specific common plant diseases, fungal and bacterial culturing techniques from plant tissue samples, and one or more pathogen inoculation techniques. Nearly two thirds of lab courses (61.0 to 66.1%) provided activities on keying out or identifying a fungal pathogen, performing ELISA or similar assays, and recognizing symptoms of nutrient deficiencies. Somewhat fewer courses covered: ability to key out or identify a bacterial pathogen (56.9%), sight recognition of common insect/mite feeding symptoms (49.2%), ability to make media and reagents from a recipe (43.3%), ability to key out or identify a nematode (42.4%), and ability to perform DNA extractions and PCR (38.3%). As with content knowledge, many of these skills were covered at a “minimal” level, and not as a course learning objective (Fig. 2). Other types of skills reported by instructors (write-in answers) included real time PCR, microscopy, experimental design, disease assessment, field diagnosis, and data analysis.

Knowledge and skills content in courses did vary somewhat by type of department or by the instructor’s educational background, but not by the instructor’s current research area. Though not significant at $\alpha = 0.05$, if a department had “plant pathology” in the department name, introductory courses were more likely to have a lab component (χ^2 , $P = 0.07$). Within laboratory courses, there was a tendency toward greater emphasis on bacterial culturing techniques ($P = 0.05$), bacterial identification ($P = 0.05$), and nematode identification ($P = 0.06$) if the department had “plant pathology” in the name. Courses in departments without “plant pathology” in the name had significantly higher mean scores for coverage of several general subject areas ($P < 0.05$), indicating that they were more likely to be covered, and/or more likely to be considered a course learning objective. These general subject content areas were: the disease cycle, principles of biotechnology, abiotic problems, and fungal diseases.

If the course instructor held at least one degree in plant pathology, the mean scores were significantly higher ($P < 0.05$) for coverage of epidemiology, fungal culturing, bacterial culturing, and plant pathogen inoculation techniques, and trended higher ($P = 0.08$) for coverage of nematode biology, than if the instructor’s degrees were in other fields. Among those instructors who indicated that they were currently conducting research, the area of research (plant pathology versus other subject areas) did not have a significant relationship with mean scores for any course content area.

Regardless of the content included in their own courses, instructors generally valued laboratory skills, research skills, and soft skills as components of introductory courses. When asked to rate the value of these components on a 1 (not important) to 5 (critically important) scale, the mean rating for plant pathology-related laboratory skills was 4.42, and only 1.7% of respondents scored this component at less than a “3” rating. General research skills received a score of “3” or higher by 84.7% of instructors, with a mean score of 3.42, and soft skills received a score of “3” or higher by 78.0% of instructors, with a mean of 3.31.

Employer expectations: What do employers expect from graduates who have taken a plant pathology course? The data indicate that when an applicant lists an introductory plant pathology course on their transcript or resume, employers commonly expect strong or comprehensive knowledge for general plant pathology concepts such as Koch’s postulates, disease cycles, common diseases, and general pathogen biology at the time of hire (Fig. 3). More specific content knowledge areas such as plant defense mechanisms, resistance genes, and pathogen taxonomy were less broadly expected; however, on a five-point scale, where 1 was “no knowledge expected” and 5 was “comprehensive knowledge expected,” every listed topic was rated at a level of 3 or higher by at least 40% of employers. Similar to content knowledge areas, employers indicated higher expectations for broad skills, such as media production and culturing techniques, and placed less emphasis on specific skills such as the ability to perform specific assays or to key out various pathogens to the genus level (Fig. 4). However, with the exception of keying out or identifying

Fig. 1. Most common topics covered in introductory plant pathology courses. Topics were provided by the survey, and respondents ranked them for 74 courses as “not covered,” “covered,” or “covered as a learning objective.” The figure shows the percent of courses in which each topic was covered (first bar, total of both “covered” and “covered as a learning objective” responses) as compared with the percent in which the instructor identified the topic as a learning objective (second bar).

bacteria and nematodes, all other skills were rated at a level of 3 or higher on a 5-point scale by more than 50% of employers, indicating that at least general competency in these skills is broadly expected.

Employer desires: Coursework, knowledge, and skills. In order to determine what curriculum components may be most valuable for student professional development and work readiness, employers were asked to rate the importance of various knowledge and skill areas, regardless of whether or not a given employee had completed a course in plant pathology. First, employers were presented with a list of 29 specific course topics, plus three write-in fields, and were asked to rate the importance of each course on a 5-point scale, where 1 was “not important” and 5 was “critically important.” Microbiology, statistics, and science writing received the highest mean scores among the courses presented (Fig. 5). Other courses with mean scores of 3.0 or greater on the 5-point scale were, in descending order: ethics, plant production (agriculture), plant physiology, soil science, plant nutrition, entomology, general chemistry, general genetics, plant production (horticulture), and plant anatomy. Of 10 employer write-in courses, eight received more than one mention: mycology (four respondents), IPM/principles of disease management (two respondents), and writing/communications (two respondents). The course question was followed with an additional list highlighting six knowledge areas that we considered likely to be included within multiple different courses on the original list, but perhaps not as likely to be widely offered as entire courses, such as organic production, IPM, and business principles. As with the first list of broader courses, employers rated the importance of these highlighted knowledge areas on a 1 to 5 scale and had the opportunity to write in up to three additional topics. The highest-rated additional knowledge areas were scientific method/process, principles of IPM, and domestic agricultural production systems (Fig. 6). Each

of these areas was rated at 3.0 or greater by over 70% of employers, indicating a broad desire for employee knowledge. Other broad knowledge areas noted in the write-in category were experimental design (two mentions) and regulatory plant pathology (one mention); the remaining write-ins were all single mentions, and listed either specific skills or knowledge assessed elsewhere in the survey.

When asked about skills that they would like to see at the time of hire, employers emphasized soft skills such as teamwork, communication, time management, multicultural awareness, critical thinking, and adaptability (Fig. 7). Employers were presented with a list that included 10 plant pathology related skills, two more general laboratory skill sets, 14 general work/soft skill sets, and three write-in fields. As above, they ranked each skill on a 1 to 5 scale, with 5 being the most important. The top rated skills, with mean scores >4.4/5 and 100% of employer ratings at 3 or higher, were: teamwork (ability to work collaboratively), adaptability (ability to redirect efforts and/or work in a variety of situations), listening (ability to take verbal directions), interpersonal communication, and time management (ability to budget time, prioritize, and complete tasks on schedule). The least-sought skills were ability to key out or identify specific types of pathogens to genus level (mean scores 2.18 to 2.48, rated 3 or greater by 39 to 53%), and fluency or proficiency in a foreign language (mean scores 1.96 to 2.05, rated 3 or greater by 25 to 27%). When skills were analyzed by sector, we observed significant differences among sectors for five skill sets: bacterial culturing, DNA extraction/PCR, media and reagent preparation, computer skills, and writing ($\alpha = 0.05$; the same significance profile was obtained by both ordinal logistic regression and Wilcoxon nonparametric analyses). In pairwise *t* tests, the private sector showed lower mean scores than government employers for bacterial culturing and writing skills, and lower value than both government and academic sectors for

Fig. 2. Most common skills covered in introductory plant pathology courses. Skills were provided by the survey, and respondents ranked them for 74 courses as “not covered,” “covered,” or “covered as a learning objective.” The figure shows the percent of courses in which each skill was covered (first bar, total of both “covered” and “covered as a learning objective” responses) as compared with the percent in which the instructor identified the skill as a learning objective (second bar).

DNA extraction/PCR and media and reagent preparation, while government sector employers had lower mean scores for computer skills than private and academic sectors. Among 55 respondents who opted to write in specific desired software proficiencies, the majority listed Microsoft Office products, either as the complete suite (47.3%), or as specific components (49.1%), of which Excel was the most frequently cited (47.3%). Statistical software was listed by 16.4% of these respondents, but no single software package was universally favored; there were four software packages named among the five

respondents who listed a single, specific statistical software for which proficiency was desired, and the remainder did not specify. Other listed proficiencies with more than a single entry included database management software (7.3%) and an application development platform (3.6%). Among 45 respondents who opted to write in specific desired laboratory equipment proficiencies, nearly half (48.9%) listed microscopes, 28.9% listed autoclaves, 22.2% listed controlled work spaces (laminar flow or fume hoods, biosafety cabinets), 17.8% listed centrifuges, and 15.6% each listed pipettes/micropipettes and

Fig. 3. Content knowledge expected by employers prior to any on-the-job training, when an entry-level applicant lists a "general" or "introductory" plant pathology course on their transcript or list of relevant coursework. Content areas are listed in descending order by mean expectation.

Fig. 4. Skills expected by employers prior to any on-the-job training, when a "general" or "introductory" plant pathology course is listed on an entry-level applicant's transcript or list of relevant coursework. Content areas are listed in descending order by mean expectation.

thermocyclers/PCR equipment. Other equipment with more than a single entry included pH meters, spectrophotometers, tissue lysers/grinders, vortexers, electrophoresis rigs, and HPLC equipment.

To investigate the value placed on various experiential learning opportunities, employers were asked to rate several additional experiences and curricular components, including several types of work experience, research experience, and international study. Hands-on experience (employment, family business, volunteer work, etc.), internships, and research experiences in a plant science discipline were rated highest, with mean scores greater than 3.5 on a 5-point scale (Fig. 8). Discipline-related work and research experiences were valued over similar experiences gained outside of the plant science disciplines, but all types of work and research experience were rated at a 3 or higher by over 80% of respondents. Having a multidisciplinary program of study was rated as more important than leadership in a student organization or international study experiences.

Comparative results: Alignment of instructor emphasis with employer expectations. In *t* tests comparing the teaching of concepts and skills (not covered, minimal coverage, or covered as a learning objective) with employers' expectation that a student who has completed an introductory plant pathology course will possess each type of content knowledge and skill, instructors' emphasis on teaching particular skill sets differed from employer expectations in several areas. Among those surveyed, instructors placed greater emphasis than employers on mastery of the disease cycle concept ($P < 0.01$),

fungal pathogen biology ($P < 0.01$), host resistance ($P = 0.03$), common fungal diseases ($P = 0.01$), fungal structures ($P = 0.04$), and cultural control of plant disease ($P = 0.03$), while employers placed higher overall emphasis than instructors on DNA extraction and PCR ($P < 0.01$), media preparation ($P < 0.01$), sight recognition of nutrient deficiencies and insect/mite damage ($P < 0.01$), nematode identification ($P = 0.01$), bacterial taxonomy ($P = 0.04$), and ability to key out or identify bacterial pathogens ($P = 0.03$). The differences in mean ratings between instructors and employers were generally small (less than 0.2 points on a 1 to 3 scale, or less than 10%). However, differences exceeded 0.3 points (15%) in five areas: sight recognition of common nutrient deficiencies, sight recognition of insect/mite feeding symptoms, ability to identify nematodes (to genus level), ability to perform DNA extractions and PCR, and ability to make media and reagents from a recipe. All five of these "large gap" differences were in skills, rather than content knowledge.

Employer laments: In what knowledge and skills do employers find recent grads lacking? In an open-ended question, employers were given the opportunity to identify any knowledge or skills that they perceived as lacking among job applicants and new hires; 23 participants did not answer this question, 11 specifically answered that there were no deficiencies in knowledge/skills or that they felt everything had been well-covered previously in the survey, and 57 participants listed one or more concerns, totaling 142 individual comments. The majority of responses highlighted deficiencies in soft skills, with 55.6% of the comments pertaining to non-discipline-

Fig. 5. Additional types of coursework employers would like to see at the time of hire in entry-level employees entering with a BS degree, whether or not the employee has completed one or more plant pathology course. The importance of each course topic was rated on a 5-point scale where 1 was "not important" and 5 was "critically important." Each bar represents the mean score and the error bars represent the standard error of the mean.

specific attributes or skills. Among the specific soft skills listed, the most frequent (14.1% of total comments) fell within the category of communication skills, with 7.7% specifically calling out writing skills (including general composition, grammar and spelling, organization, and record-keeping). Attributes related to work preparedness (including work ethic, task focus, interest in the job, and realistic expectations regarding schedules, compensation, etc.) accounted for 9.9% of all comments. Other repeatedly mentioned soft skills and attributes included willingness/ability to learn on the job (6.3%) and time/task/project management skills (4.2%). Other specified soft skills

with more than one mention included teamwork, initiative, informational skills (literature search and synthesis), adaptability, attention to detail, and patience/diligence.

Among the discipline-specific perceived deficiencies, the largest number of comments fell into the category of foundational knowledge in general biology, plant biology, and/or plant pathology (12.0% of total comments), with 4.2% of comments specifically mentioning a lack of applied knowledge, as exemplified in three separate responses which included some variation of “knowing what a plant looks like.” A few respondents further qualified their perceived

Fig. 6. Additional types of knowledge employers would like to see at the time of hire in entry-level employees entering with a BS degree, whether or not the employee has completed one or more plant pathology courses. Content areas are listed in descending order by mean expectation.

Fig. 7. Skills employers would like to see at the time of hire in entry-level employees entering with a BS degree, whether or not the employee has completed one or more plant pathology courses. Content areas are listed in descending order by mean expectation.

knowledge gaps. For example, one respondent acknowledged that their organization's location impacted the field of applicants they are able to attract, indicating that the lack of agricultural or plant pathology curricula at regional universities has resulted in an applicant field consisting mostly of graduates who were not able to find a job in their own major field and have simply had no exposure to agricultural plant sciences. Another respondent attributed the lack of knowledge to a generational trend, wherein recent graduates have deemphasized retention of factual knowledge, in general, as a result of having constant access to the internet.

Laboratory skills constituted the second-most cited discipline-related deficiency, at 9.2% of total comments. Most respondents in this group mentioned a general unfamiliarity with laboratory equipment and how to use it. Where specific examples were given, they included: pathogen isolation and culture/aseptic technique (five mentions), microscopy, pipette use, and diagnostic methods (two mentions each), accurate measurement, DNA extraction, PCR and electrophoresis, pathogen identification, pH meter and spectrophotometer operation, planting (seeds or transplants), proper use of glassware, and proper post-experiment cleanup (one mention each).

Statistical and math skills (including laboratory calculations, basic statistics, and experimental design) took third place in frequency among discipline-specific citations, at 5.6% of total comments. The remainder of respondent-identified deficiencies fell into two highly heterogeneous categories: job-specific knowledge and skills (e.g., dendrology, mycology, soil chemistry, regulatory plant pathology, etc.), and field work (e.g., operation of field equipment, pesticide handling, soil sampling, plant identification, etc.).

When asked for suggestions to improve the quality of entry-level applicants, 27 participants offered one or more specific suggestions. The most frequent suggestion (16 respondents) was to increase opportunities for students to engage in hands-on experiences, including internships (six mentions), research experiences/courses (three mentions), fieldwork (two mentions), industry field trips or "shadow" programs (one mention each), and greater emphasis on skills within coursework (three mentions). One industry sector employer also suggested that internship opportunities could be improved if industry rewarded employee participation in mentoring interns during performance evaluations. Another respondent suggested offering summer

practicum courses, in which faculty and students would offer clinics at local farms or gardens. The second most frequent category of suggestions involved increasing the breadth or balance of skills; three respondents mentioned development of one or more soft skills, and another three addressed breadth and rounding in a more general sense, including work "across disciplines" and educations that are "flexible ... that will allow them to migrate and evolve." Five respondents mentioned availability, encouragement, or requirement of specific courses, including basic botany, mycology, statistics, plant pathology, and regulatory plant pathology. Finally, two participants suggested changes in recruitment or admissions strategies: one recommended increased outreach at the middle and high school levels, and another suggested that college admissions should emphasize work experience over extracurricular activities.

In a separate write-in question, 25 employers offered one or more suggestions for improving interactions between university personnel and employers outside of academia, a factor that may impact both curriculum alignment with employer needs and the availability of student experiential learning opportunities, such as internships and field trips (objective vi). Most responses revolved around simply engaging with industry professionals in a variety of contexts (e.g., at professional meetings or through commodity groups) and reaching out with invitations to participate in academic functions (guest lectures, networking events, recruitment fairs, etc.). Two respondents suggested reaching out directly to local industry employers and simply asking what they are looking for in employees, while two others suggested creating more formal opportunities for exchange between universities and industry, such as open forums or roundtable discussions. Others suggested increasing student field trips to industry sites (three mentions), increasing internship opportunities (four mentions), and making it easier for industry personnel to secure courtesy appointments within academic institutions. In a simple yes/no question, 79.8% of respondents indicated they would be interested in visiting a university campus to talk with students about employment in their sector or field.

Conclusions

A recent McKinsey survey (August-September 2012) found a 38% gap between U.S. educators' and employers' views of graduate readiness for entry-level positions in the job market: 87% of

Fig. 8. Additional types of experiences employers would like to see at the time of hire in entry-level employees entering with a BS degree, whether or not the employee has completed one or more plant pathology courses at the time of hire. Employers rated the importance of each type of experience on a 5-point scale where 1 was "not important" and 5 was "critically important." Each bar represents the mean score and the error bars represent the standard error of the mean.

educators agreed that their graduates were “adequately prepared for entry-level positions in their chosen field of study,” while only 49% of employers agreed that “employees we hired in the past year have been adequately prepared by their prehire education” (Mourshed et al. 2012). The percentage was even lower for the agricultural sector, in which only 37% of employers agreed that new-hire employees were adequately prepared. Further, employers in the McKinsey survey cited this skills gap as a factor in their hiring decisions, limiting employability for recent graduates. Among U.S. employers who had entry-level vacancies, 45% cited lack of skills among new graduates as a reason that current vacancies were unfilled. As educators in plant pathology, we would like to think that we are preparing our students well for their futures in plant science fields, but there has been no previous effort to examine the content of undergraduate plant pathology courses and explore potential gaps between our course content and employer needs and expectations for these courses. This research represents an effort to provide plant pathology educators with an unbiased assessment of our efficacy in preparing students for the agricultural work force, as well as to establish a foundation for future conversations about our plant science and plant pathology curricula.

The instructor survey deployed for this research reached a broad, but not exhaustive sampling of undergraduate general plant pathology courses being offered across the U.S. and its territories. The authors know of at least nine additional courses that were not represented, due to nonparticipation by instructors. Although we were unable to achieve 100% participation from U.S. instructors, the responses did achieve a cross section of various institution types (land grant, research, liberal arts, etc.), academic departments, and instructor expertise, which we believe sufficient to generate a profile of undergraduate introductory plant pathology courses as they are currently offered. Likewise, our employer survey distribution did not reach every potential type of employer that might be expected to hire BS-degreed graduates who have taken a plant pathology course, but we achieved a cross section of employment sectors that included industry, government, academic, and nonprofit entry-level positions among employers who hired and/or supervised a total of over 950 such employees.

Among the undergraduate courses described by survey participants, three quarters met a degree requirement for one or more majors at that university, and only 20% of courses surveyed were designed specifically for plant science or plant pathology majors and graduate students. These data together corroborate our observations from the University of Wisconsin and University of Florida that undergraduate plant pathology courses are important service courses for the biological and agricultural sciences. We found that there is a high level of consistency in content knowledge taught in introductory plant pathology courses across the country and that the content knowledge generally aligns well with employer expectations for students who have taken these courses. While topics are largely the same across courses, there is variation in where emphasis is placed, and in the manners in which students engage with course content.

Caution should be used when interpreting significant differences between instructor emphasis and employer expectations, particularly in areas where instructors have placed greater emphasis on concepts or skills than did employers. While instructors aim to prepare students broadly for a wide range of future needs, employers may be more narrowly focused on specific knowledge and skills relevant to their work functions. Due to these differing objectives, employer expectations may be lower for areas not related to their own expertise, regardless of the educational value of the topic. However, where employers report significantly higher expectations than the instructors’ stated emphases, we need to consider what gaps in course and curriculum content may be indicated. It is noteworthy that all of the questions on which employers reported much higher expectations than instructors indicated emphasis (significant, and with greater than 0.3 points mean difference) related to skills rather than content knowledge. It would appear that general/introductory courses are doing a better job at content coverage

than at providing hands-on practice and skills development. Some might argue that this is the proper role of university education, that the purpose of a college education is to provide well-rounded intellectual development, not to impart vocational training or bestow a marketable degree (Faust 2009; Kidd 2005; Molesworth et al. 2009). However, the vast majority of students seeking a bachelor’s degree expect to matriculate to either employment or a graduate program (e.g., The Ohio State University 2015; University of Florida 2017; University of Wisconsin – Madison 2016). For those who expect to transition directly to full-time employment, appropriate skills are critical to their success in a highly competitive job market. In order to serve the educational needs and expectations of these students, we need to balance the philosophical training with desired skill sets, to deliver what some have termed the “professional education” (Grubb and Lazerson 2005). Additionally, providing hands-on practice with the skills relevant to the field is not just vocational education; it is a more effective way to facilitate student learning. One of the driving forces behind recent recommendations for “active” and “inquiry-based” pedagogies is the repeated confirmation that authentic, practice-based experiences reinforce learning (Freeman et al. 2014; Michael 2006).

The plant pathology courses represented in the survey are predominantly conducted in a traditional “lecture and lab” manner, with lectures providing the bulk of content knowledge transfer and labs providing the opportunity for interaction and skills development. Laboratory components can be critical to student learning and success in courses, and often provide the only opportunities students will have to develop the hands-on skills associated with the course content knowledge. Freeman et al. (2014) noted that students in traditional lecture classes were 1.5 times more likely to fail than students in active learning classes, and research across multiple STEM subjects and age groups has shown that hands-on activities increase gains in knowledge and/or skills over passive learning modes, such as lectures and instructor demonstrations (Glasson 1989; Grober et al. 2004; Hake 1998). Lab courses require additional resources in terms of materials, facilities, and instructors, and it may be a challenge in the near future to maintain these courses as budgets shrink at universities across the country. From 2008 to 2016, state spending for public two- and four-year universities was reduced by 18% per student on average, but with reductions of more than 30% for some states (Mitchell et al. 2016). Limited resources for teaching laboratory courses may contribute to our observed lower probability of an introductory plant pathology course including a laboratory if it is offered in a department that does not identify as a plant pathology department. Given limited resources, it is likely that a department that specifically includes “plant pathology” in its name will be more inclined to prioritize teaching resources toward laboratory-supported introductory courses, while those that do not will be more inclined to prioritize laboratory support for courses that more directly align with their own programmatic identities. It is encouraging to see that despite these constraints, plant pathology departments and instructors still value lab components in their courses, and it is clear from this work that employee preparation in the kinds of authentic skills desired by employers would be greatly benefited by not just maintaining but enhancing laboratory experiences.

Despite our finding that laboratory-based courses still predominate among introductory course offerings, lack of basic lab skills remains a problem among BS degree graduates in plant sciences, and many of the specific skills that employers expect from students who have taken an undergraduate plant pathology course are not broadly emphasized by instructors of those classes. The general deficit in laboratory skills among college graduates in plant sciences cannot be attributed to, and will certainly not be remedied within plant pathology courses alone. However, recognition of this skills gap should help us determine what we emphasize and how we design our courses. Students who take plant pathology courses have also generally taken multiple laboratory courses in biology and chemistry, and often several others, such as microbiology, entomology, and soil science. Simply taking lab courses, however, does not

guarantee development of laboratory skills. The laboratory exercises themselves make a difference; so-called “cook-book” labs that demonstrate key concepts in a course may be better than no lab at all (Bates 1978), but lab experiences that engage students beyond the level of following directions and observing results tend to produce deeper learning and better skills development (e.g., Gallet 1998; Lord and Orkwiszewski 2006; Reif and St. John 1979; Rissing and Cogan 2009; Roth and Roychoudhury 1993; Tobin 1990). We may need to re-examine the specific exercises and activities deployed in our labs to ensure that we are making the most of this valuable resource.

The most commonly cited areas, aside from lab skills, in which recent graduates are not meeting employer expectations were related to work ethic/work readiness, communication, writing and record keeping (includes keeping a lab notebook), and statistical analysis and synthesis (including experimental design). Soft skills were listed across the board as lacking, particularly in the areas of interpersonal communications and time management. Multicultural competency was highly valued by employers in our survey, but they did not place high value on any specific educational component associated with increasing student cultural competencies, such as international experience (e.g., study abroad) or knowledge of a foreign language. Either there is a disconnect between the desired outcome of multicultural competence and recognition of the kinds of experiences likely to produce that outcome, or employers simply do not care how the skills are acquired, as long as they are acquired. The skills and attributes identified as lacking among recent graduates largely overlapped with the skills and attributes that employers reported wanting to see in new employees, regardless of whether or not they had taken a course in plant pathology (e.g., communication, adaptability, teamwork, and critical thinking). Many of the comments regarding characteristics such as work ethic and expectations, and skills such as professional communications, touched on an overarching theme indicating an inability among many students to make a smooth transition from student life to work life. Employers consistently indicated a desire for new employees to show greater dedication, passion, humility, and initiative, and while numerous specific skills were mentioned, it was frequently in the context of desire for a better “balance” of skills. Several employers commented that specific skills can be taught, but characteristics such as passion for research, willingness to learn, and a drive to go the extra mile cannot.

Soft skill development among STEM graduates is a widely recognized problem, by no means unique to the plant sciences (Hart Research Associates 2015; Harder et al. 2015; PCAST 2012), and recognition of this problem led the American Association for the Advancement of Science to release an open call for change in the way biology is taught in the United States to create a more student-centered undergraduate curriculum (AAAS 2011). Others have also recognized that creating student-centered curricula alone may not be sufficient, if students do not understand the value of the skills that such curricula are designed to develop (Marbach-Ad et al. 2016). We found moderate levels of adoption of student-centered instructional techniques among undergraduate plant pathology instructors in our survey. Our resolution in examining the use of specific techniques was low, however, relegated to a self-reported assessment of use as “none, minimal, or frequent” for each of a list of recommended practices. These data provide a good general overview, but additional work would be required to fully examine the extent to which courses are employing known effective techniques for developing desired skills. More work is also needed to determine the extent to which plant science students recognize the skills that will be most valuable to future employers. In the study by Marbach-Ad et al. (2016), for example, only 45% of students placed a high value on group work, a clear mismatch with the high value placed on teamwork and interpersonal communication skills by employers in our survey, as well as others cited in the reports above. Similarly, only 66% of students in the Marbach-Ad study placed a high value on scientific writing, a skill that was among the top most cited in our survey as both desired and lacking among recent graduates. While increased adoption of known high-impact teaching practices for improving soft skills can

and should be employed for plant pathology undergraduate education, these techniques demand more work from students than traditional lectures and “cookie-cutter” labs, and instructors often meet initial resistance from students who are accustomed to passive learning. Thus, further work is also needed to identify more effective means of communicating the importance of these skills to students as we ask them to invest additional time and energy in their development. Increased participation in internships and other opportunities for students to interact with employers, such as site visits and round-table forums, are currently underused activities that might be effective in this regard.

These survey results highlight several key areas in which universities and professional societies, such as APS, may consider directing efforts to support preparation of undergraduates in the U.S. to be not only better-prepared candidates for the work force but also stronger contributors to the fields of plant pathology and plant science at large. Universities (at the department and/or college levels) and professional societies (including disciplinary, as well as industry and commodity-centered) could play a greater role in supporting consistent connections between educators and employers. There have been efforts in this regard, including a 2009 APS Workshop that engaged professional society representatives, employers from the private and government sectors, and academic unit leaders in a discussion of emerging issues in plant science education and workforce development (MacDonald et al. 2009). However, these efforts have not yet yielded widespread, sustained solutions to either the dearth of opportunities for student interaction with employers or the perceived skills deficits identified by employers.

At the classroom level, many instructors are not familiar with, or not sufficiently confident to employ, many of the student-centered practices known to enhance learning and skill development. Game-based learning, citizen science, inquiry-based learning, and flipped lectures were all instructional techniques examined in this survey that were unfamiliar to some instructors and/or underutilized. In postsurvey informal interviews, several instructors noted that pedagogical terminology was generally unfamiliar to them, and they were uncertain whether one or more of their current activities might fit within these named practices. Given university teaching faculty’s notoriously busy schedules, many instructors may simply not seek out educational research to inform their teaching practices, and bringing that information to instructors, within their current range of utilized resources, may be helpful in increasing familiarity and use. The APS-net Education Center is a ready platform for such resources, and we recommend strengthening the resources available specifically to help instructors transition to more practice-based and student-centered teaching approaches. Similar platforms are available at many universities, but providing discipline-specific lesson plans and curriculum recommendations for plant pathology is a role best served at the national society level.

Employers in our survey suggested that internship experience was both valuable and lacking among recent graduates and also recommended increasing student field trips and site visits, as well as academic-industry collaborations in general. Internships are among the most widely recognized and potentially valuable high-impact practices for undergraduate education (Kuh 2008), yet they are also plagued with a reputation for variability in quality and accessibility. Strengthening relations between academic departments and nonacademic employers could help in clarifying goals and expectations for internships, and increase the number and diversity of internship opportunities available. Several of the employers in our survey indicated that their current interactions with academic departments occur on an individual basis, with specific professors with whom they happen to have an association. While effective at a small scale, this sort of individual connection can be unstable and limited in scope: students who do not know the individual professor may have no access to the opportunities, regardless of their suitability, and if either individual changes positions, the entire connection between the academic department and company/agency may be severed, cutting off any further internship or other student interaction

opportunities. Academic departments, professional societies, and commodity groups are well positioned to support broader networks, bridging academia with private and government employment sectors. We concur with employer comments in our survey suggesting that such entities consider hosting roundtables, discussion groups, and networking events, specifically designed to increase connections among educators and stakeholders. We would also add that professional societies could provide informational infrastructure, via existing websites, to connect educators and employers who may be interested in engaging but have no existing contacts to do so.

It is probably fair to say that most academic personnel are working hard to ensure that our curricula will attract and engage diverse, highly motivated, capable students and will provide them with the competencies needed to be successful in their careers and to contribute to solving plant-related problems in a rapidly changing world. Most of those instructors whom we surveyed also agreed with employers on the types of skills that are needed, regardless of the specific skills that they emphasized within their own courses. Actualizing improvements in student preparation for the workforce, however, is a complex process, constrained by funding (needed for teaching laboratory equipment and supplies, teaching personnel, transportation for field trips, organization and hosting of internship fairs and other employer engagement events), institutional procedures and policies (which may constrain the changes that can be made within degree programs, the requirements that may be defined for a degree, and the flexibility that students may have in selecting courses to achieve a broad skill set), and intra- and interdepartmental relationships (which determine the influence that a department can exert to ensure that courses taught in other departments are meeting programmatic needs, and the extent to which course content may be coordinated within a degree program). To the extent possible, we suggest that unit leaders encourage and support coordination across courses within a degree program, to ensure that critical skills are not “falling through the cracks,” as each instructor develops their own course objectives. The most common reasons that instructors in our survey cited for not including skills that they considered valuable revolved around time constraints and course focus. No single course can cover every skill, so we need coordinated efforts to ensure that critical skills are distributed across required courses and that they are sufficiently repeated and reinforced from one course to another.

Finally, we suggest that leaders across all sectors consider the influence that they have to create motivations for action. None of the work that needs to be done to improve student preparation will be initiated or sustained by professionals whose job descriptions and evaluation criteria make this work superfluous, or worse, a detriment to their own careers. Including educator-employer liaising in one or more department members’ job descriptions, or otherwise creating incentives for investment would help to ensure that the work that goes into developing and maintaining these relationships and organizing interaction opportunities is recognized and rewarded. Regardless of the sector in which you work, the future of our discipline relies upon having a well-trained student population, and improving the preparation of the next generation of plant pathologists is a labor worthy of our best efforts.

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