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REVIEW

A fresh look at graduate education in Plant Pathology in a changing world: global needs and perspectives

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Abstract

Among the many responsibilities of the worldwide scientific community are advancing the knowledge base that underpins each scientific discipline, addressing the pressing scientific issues of the day (e.g., emerging infectious diseases, food security, and climate change), and perhaps most importantly, educating and training subsequent generations of scientists. Yet, around the globe, advances in scientific and communications technology, proliferation and mining of data, and increasing financial constraints of university systems have led to fundamental changes in our institutions of higher learning. Increasing emphasis on interdisciplinary and multidisciplinary approaches to problem solving in agriculture add to the complexity of providing robust preparation for the plant pathologists of the future. Thus, as the U.N. recognizes the year 2020 as the *International Year of Plant Health*, it is fair to ask if current approaches to graduate education in plant pathology are adequate to meet current and anticipated challenges and if the outcomes can be improved.

Keywords Plant pathology graduate education · Interdisciplinary · Multi-disciplinary · Science vs. technology · Critical thinking

Introduction

Although the United Nations General Assembly declared 2020 the *International Year of Plant Health* the practice of plant pathology emerged in its earliest and simplest forms during the Neolithic era (7000–10,000 years ago) as humans began to stabilize their lives and secure their food sources by the cultivation, domestication and improvement of native plants. In that era practices to maintain plant health were developed by trial and error and passed to the next generation by word of mouth. Since then, plant pathology has evolved in step with the expansion and increasing sophistication of agricultural production and interest in the well-being of the natural environment. More formalized attention to plant pathology education, too, has evolved, involving different approaches in different parts of the world.

Among the many responsibilities of the scientific community are advancing the knowledge base that underpins each scientific discipline, addressing the pressing scientific issues of the day (e.g., emerging infectious diseases, food security, and climate change), and perhaps most importantly, educating and training subsequent generations of scientists. That scientists and society take this latter responsibility seriously is evident in the many programs offered by universities, scientific societies (e.g., the American Phytopathological Society, the International Society for Plant Pathology), charitable foundations (e.g., Bill & Melinda Gates Foundation), and funding agencies (e.g., National Science Foundation, USDA National Institute of Food and Agriculture) that support and promote the education of young people in science, technology,

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engineering and math (STEM). In a technology-driven world with a knowledge-based economy, declining interest and enrollment in STEM disciplines (Marginson et al. 2013) is rightfully of serious concern. Education is about the acquisition and application of knowledge while training is about increasing skills.

Many thoughtful discussions of the issues and challenges related to plant pathology education have been published (Brown 1945; Eastburn and D'Arcy 2010; Gisi 2010; Gullino 2009; MacDonald et al. 2009; Merrill 1978; Richter et al. 2018; Sands 1992; Schumann 2003; Vincelli 2005) although most of these have focused primarily on undergraduate studies. Two (MacDonald et al. 2009; Gullino 2009), however, both published a decade ago, addressed the particular aims, approaches and outcomes of graduate education leading to the M.S. or Ph.D. in plant pathology (or their equivalent). Since that time worldwide advances in scientific and communications technologies, proliferation and mining of data, and increasing financial constraints of university systems have led to fundamental changes in our institutions of higher learning. Thus, as the U.N. recognizes the International Year of Plant Health, it is fair to ask if our approaches to educating the next generation of plant pathologists are adequate to meet current and anticipated challenges and if the outcomes can be improved.

In this paper, six plant pathologists from five different countries (the United States, Italy, Israel, Australia and New Zealand), whose combined longevity in plant pathology graduate education approaches 190 years, reflect on the changes, current state and future of graduate education in plant pathology, with a focus on international perspectives. Although each of us has lengthy personal experience with the issues of plant pathology graduate education in our own countries we lack sufficient personal knowledge to draw parallels or conclusions about the situation in other nations. However, by introducing some unique considerations from several of our countries we hope to present an international perspective appropriate for the International Year of Plant Health.

The evolution of traditional graduate education in plant pathology around the world

Although humans have cultivated plants for centuries, focused scientific study and literature in plant pathology began only in the seventeenth century and came to flourish in the 1800s. As institutions of higher learning began to broaden their purviews beyond the education of relatively wealthy students in the liberal arts and traditional sciences, practical subjects including the agricultural sciences were added to university curricula in an increasing number of countries and regions. Since then plant pathology units have proliferated in academic institutions around the world. In the United States, agricultural education beyond the undergraduate level is deeply seated in an integrated system of land grant colleges established in 1862 by the Morrill Act with the purpose of teaching agricultural subjects and the mechanical arts (Earl et al. 1995). Later legislative acts added research and extension to the land grant mission and provided funding for the support of these efforts. The presence of at least one land grant college in each state, United States territory and the District of Columbia, provided breadth as well as depth in teaching and addressing agricultural issues across the country. Over the past century the trajectory of the discipline of plant pathology in United States institutions of higher learning has been described in the previous section.

In the early days most agricultural universities had a free-standing plant pathology department. In the United States, as well as in other countries, a variety of discipline-relevant courses (plant pathology, physiological plant pathology, plant disease management, bacteriology, virology, mycology, nematology, post-harvest pathology, and others) were offered, often as requirements or selected electives to fulfill specific M.S. or Ph.D. curricula, and graduate students gained broad, practical knowledge of crops and their diseases and pests. Graduate plant pathology degrees generally also required some coursework in related disciplines such as microbiology, genetics, soil science, entomology, and statistics. In contrast, the 'English-style' graduate education system, common also in many other countries, generally consists of two to three years of graduate research often focused on a specific pathogen-host combination and additional course work is neither required nor common. This system has an advantage of specialty focus, and a disadvantage of providing limited experience with other pathogen-host systems.

Over time, due to financial constraints and the resulting downsizing faced by most universities, many plant pathology units have been merged or combined into larger, presumably more cost-effective multi-disciplinary departments (e.g., Entomology and Plant Pathology, Plant and Soil Sciences, Plant and Environmental Sciences, Bioagricultural Sciences and Pest Management). In many universities, as a consequence, the discipline of plant pathology has been subsumed within a larger context, with mixed consequences. For example, none of New Zealand's nine universities still maintains a traditional 'Plant Pathology' department or its equivalent. NZ higher education institutions have replaced departments as the fundamental organizational and administrative university entity and it is now difficult to find the term 'plant pathology' on university websites; rather the relevant disciplinary scope is defined as biotechnology, biodiversity, and biosecurity (Anon 2019a) or microbiology (Anon 2019d), or is held within the School of Science (Anon 2019b).

On one hand, the emphasis on multidisciplinarity has had positive effects on both research and teaching. At the core of plant pathology, the plant disease triangle (McNew 1960; Agrios 2005) depicts the understanding that it is the complex interactions between a virulent plant pathogen, a susceptible host and a conducive environment that results in disease. This paradigm identifies plant pathology as an interactive and overlapping field of investigation requiring skills from a wide range of biological disciplines including microbiology, biochemistry, genetics, botany, zoology (arthropod vectors), ecology, biotechnology and bioinformatics. The spectrum of emerging pathogens and re-emerging pathogens continues to grow in both production crops and as well as in native ecosystems and requires a broad comprehension of potential causal agents and strategies to confirm hypotheses. Furthermore, the realization that our science intersects in significant ways with other disciplines not traditionally linked with plant pathology, including agricultural biosecurity, food safety, food technology, engineering and artificial intelligence, has opened new doors for productive, collaborative interactions that may be encouraged or facilitated within an interdisciplinary institutional framework. In general, during the past 25 years, although many specific traditional courses have been lost, our discipline has gained a larger profile in other sectors, with positive effects on research and teaching.

However, the gradual loss of professors and instructors proficient in teaching core and elective graduate plant pathology courses, and mentoring M.S. and Ph.D. students in rigorous and meaningful, practical research experiences, is concerning. Multi-disciplinary blended departments may still offer graduate degrees in plant pathology, but many are struggling to maintain the full complement of faculty positions needed to support the offering of once-required coursework for these diplomas. For example, most European, Israeli and New Zealand universities no longer require or provide for a wide range of course selections for graduate plant pathology degrees. Rather, plant pathology-relevant courses are offered in units of agricultural science, plant science, plant biotechnology, microbiology, immunology, food science, food technology, environmental sciences and biological sciences. In Italy, as well as in many other European universities, a M.S. graduate in agricultural science, having taken only one course in plant pathology and one in plant disease management, has a general background but little practical experience. In the most advanced European universities teaching is closely connected to research activities rather than to formal coursework. The majority of Israeli Ph.D. studies focus on specific molecular mechanisms targeting small biological processes in the microorganism or the plant, with little view of the whole pathogen plant system, or relevance to field application. Interestingly, concerns about the "loss" of plant pathology as the science moves toward multidisciplinarity and specialization are not new. In 1963 J.C. Walker wrote: '*there will always be plant disease problems and crop losses from diseases. What I am concerned about is that these 'specialty' groups will lose plant pathology*'. Weinhold (1996) further addressed this paradigm by stating '*plant pathology is thus placed in jeopardy because there is a loss of contact with disease problems, which are the reason for our existence*'. These statements are as relevant today as in 1963 and 1996 and the needed balance can be achieved by driving an interdisciplinary approach.

Often, as faculty members specializing in applied, field-related subject matter retire they are either not replaced at all or are replaced by new faculty members working in the fundamental sciences including genetics, molecular plant pathology, bioinformatics, and other emerging disciplines. Furthermore, the growth of molecular biology and an increasing preference for laboratory research over field research has produced a generation of researchers and teachers unfamiliar with applied plant pathology practice, a trend reflected in the specializations and preferences of many of our graduates. Many institutions and departments of plant pathology have reduced or eliminated laboratory sections associated with the foundation courses (e.g., bacteriology, virology, mycology, etc.), thus precluding direct experiential hands-on learning and narrowing the base of knowledge of their own discipline. Some of the techniques once considered essential for a plant pathologist, such as aseptic culturing, or working in a containment facility, are far less often demonstrated or practiced at university. The focus has shifted to learning computer/server-based skills that are being increasingly expected of contemporary plant pathologists, including the ability to interpret metagenomic and other complex nucleic acid and/or metabolic data sets to propose and evaluate new control options. Despite the introduction of new technologies (and the potential loss of some skills) the principal of hypothesis-based research is still critical: a specific statement of prediction and a well-designed experiment and appropriate data analysis to form a valid conclusion.

Drivers of the need for change

The need to re-kindle skills for critical thinking and creative idea generation

Throughout history critical thinking has been the foundation of science. One need only read the *Phytopathological Classics* (https://apsjournals.apsnet.org/series/classics) to see the value of critical thinking to gain understanding of natural phenomena, often unassisted by technology. However, technology has played an increasing role in scientific advancement over the past few centuries, including the use of telescopes to study the cosmos in the 15th and 16th centuries (Galileo and Copernicus), the development and use of microscopes to study microbes and cell structure (van Leeuwenhoek), and the use of X-ray diffraction to unravel the structure of DNA (Franklin). More recently, high throughput nucleic acid sequencing technologies accompanied by bioinformatics software tools have provided access to, and increased our understanding of, the genetic information that governs life. Technology has facilitated rapid progress in many disciplines and allowed scientists to pursue questions that were beyond reach historically. For the past few centuries, scientific progress has largely been a function of advancing technologies. The rapid and increasing rate of technology development has underpinned dramatic scientific progress while increasing the dependency of scientific advancement on technology. Historically, this has been an integrated push-pull relationship (Fig. 1). Have we become so enamored with technology and the capabilities that it bestows, that we are allowing technology to dictate the scientific agenda and set the priorities? Do we more frequently focus funding programs on a technologies (e.g., aerial drones, geographic information systems, biotechnology) rather than the science (e.g., strategic surveillance, epidemiology, biology)? Do we more frequently hire faculty based on their skill set (e.g., genomics, bioinformatics) rather than their ideas and the scientific questions they will ask (e.g., how are human pathogenic fungi acquiring fungicide resistance from plant pathogens)?

Despite the ever-increasing role of technology as a driver of scientific progress, critical thinking has generated the most significant advancements in science and society. Einstein's theories of special and general relativities are prime examples of critical thinking, setting the agenda of thinking for decades as well as driving the development of new technologies. Critical thinking leads to better questions, more sophisticated analyses, and more profound contributions to areas of inquiry. So the question to answer in the International Year of Plant Health is, ***are we educating the next generation of scientists/plant pathologists appropriately to ensure advancement of our discipline and the successful resolution of current and anticipated challenges to plant health*?** Are we teaching critical thinking and encouraging creativity? It is not only about content; it is also about process (Sands 1992).

> *"..it is impossible to develop science without technology, or to develop technology without social and cultural openness to innovation and change. It will be noted that social expectations, technology and science interact to amplify each other in a system of positive feedback.*" Quote from Machula 1991.

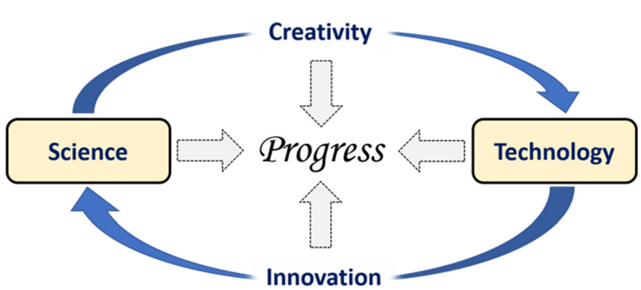

Fig. 1 The integrated push-pull of science and technology driven by creativity and innovation; balance is required to derive the greatest good

Preparing scholars versus training technologists The rate of generation of new information and knowledge has accelerated greatly, and there has also been a dramatic increase in scientific disciplines/areas of study with an explosion of new journals (on-line and print) dedicated to those new areas of study. Many curricula now contain new courses that focus on these new areas and technologies. More courses are technology-based and sometimes compete with biologically-based courses and biology-based education. One consequence is the gradual loss of plant pathologists with training in the core competencies necessary to fulfill the requirements of certain professions (e.g., diagnostics, teaching plant pathology). Will the next generation have broad context for the discoveries they encounter?

A resulting challenge is to find balance between the study of science and the study of the technologies that facilitate progress in science. The fact that some universities question whether graduate students need formal coursework as part of their degree program goes to the very heart of this discussion; is the objective of graduate education to train technologically sophisticated researchers or to prepare scholars that will advance their discipline? They are not the same thing. Should the emphasis of the Master of Science degree be the generation of scientists to conduct research, and the emphasis of the Doctor of Philosophy degree be to generate scientists to advance their discipline? It is a fundamental question regarding the balance between training technologists (M.S.) and preparing scholars (Ph.D.).

The National Science Foundation report on graduate education in the U.S. challenged universities to make graduate education student focused, providing students greater autonomy in choosing their area of focus (National Academies of Sciences, Engineering and Medicine 2018). Scientific enterprise in the U.S. is not structured to support that model; the grant systems that support our research programs determine the areas they will fund and the ideas that they will support. Most often, the ideas are generated and the research strategy identified before the student joins the program; we are awarded the funding and then recruit the students based on the project funded.

There is some merit in the graduate education model recommended by NSF, however, there are challenges to that model as well. The durations of many grant-funded research programs are less than the time required to complete a Ph.D. degree. In the United States, the majority of Plant Pathology graduate education programs are housed within land grant universities (LGUs). State and Federal support for LGUs has declined substantially over the past few decades to the point where there are very few graduate research stipends independent of specific research grants. The consequence of that model is that the funding agencies determine the area that each student will pursue and limit the depth of education by forcing the graduate program to limit the breadth of the educational experience in order to complete the research within the funding period. The consequence is a graduate education experience that is centered around completing a research project rather than on becoming a scholar; again, there is a difference with ramifications for the advancement of science.

In light of the explosive rate of new knowledge (90% of all data today was generated in the last 2 years) and the staggering rate of development of the technologies that underpin science, one could argue that preparing students that are highly skilled in the technologies and questions of the present without emphasizing the critical thinking skills necessary to formulate the most important questions for inquiry in the future is to fail at the very purpose of a graduate education, namely, preparing scholars and the advancement of science. As emphasized in the ASM report (Payne et al. 2019), focusing on critical thinking and generating scholars should be the focus of a graduate education.

> *"These challenges provide opportunities for reforming the graduate education enterprise to better align it with the needs of society and science in the twenty-first century*." Quote from Payne et al. 2019. ASM Colloquia Report.

The plant pathologist of the future

What is a plant pathologist?

The naming of a discipline is worthy of discussion. In some universities the title of plant pathology has been subsumed or replaced by newer terms such as molecular biology, biosecurity, plant health, plant protection, and biotechnology. Interestingly, some of these fields are actually derivatives of more traditional disciplines; for example, plant pathology is a key enabler for achieving the outcome of biosecurity and a key area in which molecular biology is applied for practical benefit.

The future challenges posed by plant pathogens in a complex world of climate change and diminishing resources will not be solved by relying on the skills of a single classical discipline. Interdisciplinary research is crucial and will have broad societal, environmental and economic impacts (van Noorden 2015). The next sets of scientific discoveries will occur on the boundaries between disciplines (Rylance 2015), and their translation into use will need to incorporate biological, physical and social elements. For plant pathology the new techniques and tools made possible by advances in molecular science, nanotechnology, engineering, economics, social engagement, data science and other nontraditional fields highlight the necessity of combining and synthesizing research strategies from various disciplines to accomplish an integrative purpose (Klein 2010).

Career paths in plant pathology

Many university professors see students as future researchers and train them for traditional academic careers, but graduate advisors and mentors may be overlooking careers outside academia. Positions in government and industry, international agricultural organizations (FAO, UNIDO, IFAD, World Bank), private consulting and other options abound. The agro-industry sector has been expanding and provides new opportunities to graduates in our discipline. Most universities, in preparing graduates for competitive positions, struggle to keep up with the pace of a changing work market, which demands professionals equipped with new scientific knowledge and skills in addition to career skills in oral and written communication, ethics, management and collaboration.

Preferred candidate qualities often differ with circumstances. In Italy, for instance, industry often prefers to hire M.S. graduates over Ph.D.s both because salaries are lower and because Ph.D. programs generally concentrate on research that is more basic than practical. Universities can take a larger role in providing, in cooperation with industry, lifelong leaning courses tailored on the industry need. In the United States, for example, the University of Florida offers short courses tailored toward industry needs, in which small groups of students work with an instructor to solve practical problems.

Elements of a robust training package for graduate education in plant pathology

Scientific: Traditional subjects

Although traditional topics remain vital and important in the training of graduate students in plant pathology we are facing our universities' declining capacities to provide formal coursework in all of the subject matter once required for a M.S. or Ph.D. graduate with a degree in plant pathology. One of the key challenges in the coming years will be to create the means by which our students can still acquire broad and thorough knowledge and understanding of these basic elements of traditional plant pathology. Some universities have established for-credit, open-subject, self-study course opportunities by which students can learn a particular subject area at their own pace under the guidance of a faculty member. Other universities have teamed up, offering team-taught or single-instructor courses via distance education technologies. It will become more important than ever before to continuously reevaluate the needs of our students in light of the challenges of our time and the changing requirements of employers. The impacts of curriculum change are not all negative. We should revisit them in the light of new technologies available, new trends in production systems, the effects of globalization and climate change on agriculture, and the use of big data in disease management.

Scientific: Nontraditional subjects

Our current multidisciplinary approach to scientific research and problem-solving is reflected in new subject matter that overlaps with and informs plant pathology. Some nontraditional topic areas deal with fresh ways of looking at plant systems and agricultural production, while others focus on the mechanisms and opportunities offered by new technological and analytical approaches. The points below, which are already influencing both research and practical agricultural applications, are just a sampling of topics that are already either being introduced as free-standing courses, folded into broader-reaching course topics, or offered in seminar or short-course formats for plant pathology students at many universities. Such coverage provides students with current perspectives on changing agricultural challenges and solutions.

- **Gene modification/editing**. Genetic modification via insertion of novel genes and regulation sequences, or the editing of existing genes in the plant host can be an effective mechanism to prevent disease (Collinge et al. 2010, Collinge et al. 2016, Dong and Ronald 2019). The adoption of genetically modified crops continues to spread worldwide, with 191.7 m ha planted in 70 countries worldwide in 2018, a c. 113-fold increase since 1996 (ISAAA 2018) even as the debate over how to use these new technologies continues. For example, New Zealand prohibits the growth of genetically plants in the field, whilst in Australia, the State of Tasmania is currently seeking, via the Genetically Modified Organisms Control Bill 2019, a ten-year extension to a moratorium on genetically modified organisms in that state (Anon 2019c) (in other states except South Australia GM crops are grown). These strategies should be an essential component of the education of graduate plant pathology students, complementing plant breeding, biological control and other traditional strategies for disease control (Smith et al. 2017).
- **Bioinformatics/computer sciences/big data**. Our society is now data driven, with ever-increasing emphasis on systems and tools that collect, manage and apply data. Our farming and environmental systems are now being managed through the use of decision support systems based on the capture of this data and the use of the Internet of Things (Gubbi et al. 2013). Bioinformatics in a broader context relates to the capture, management, storage, curation, integration, analysis and interrogation of polymetric data-sources (Bellgard and Bellgard 2012). The integration of new molecular and 'omics' tools, and sensors into plant pathology has resulted in ever increasing amounts of data being generated. Bellgard and Bellgard (2012) presented bioinformatics as part of the 'new world order' and a key part by which plant pathologists can assist in delivering global food and fibre security. Bioinformatics is now a common and essential component of any plant pathology research published (Noar and Daub 2016). Bioinformatics linked with big data analytics and machine learning (artificial intelligence) now provide a scalable and modular strategy for data analysis (Kashyap et al. 2016; Ip et al. 2018) and are quickly becoming the key enablers for effective research outcomes. Today's plant pathology graduates must have a sound understanding of bioinformatics, big data, data analytics and artificial intelligence and their interlinkages.
- **Phytobiomes**. *"Networks of interactions among plants, their environment, and complex communities of organisms profoundly influence plant and ecosystem health and productivity"* (quote from Beattie et al. 2016). The perception of a plant as a single, independent organism is rapidly disappearing. Just as we now understand a human body to comprise numerous different 'microbiomes' whose specific microbial makeup varies depending on the organ (skin, stomach, eye, etc), the tissue type, and the age and health of the individual, so too is the plant a complex community (a 'phytobiome') in which beneficial and harmful microbes, protozoa, insects, worms and other community members live on above- and below-ground plant surfaces, within plant interiors, and in the soil surrounding their roots (Beattie et al. 2016). All of these species influence one another, whether by competition, antibiosis, pathogenicity, synergism, triggering host responses, or other means, Understanding phytobiomes as systems, which will be critical for optimizing sustainable crop and food production and minimizing environmental harm, will require basic advances and education efforts in 'omics sciences, systems biology, microbial ecology, data sciences, and precision crop management systems.
- **Biosecurity**. The security of plant systems, whether natural (forests, rangelands, prairies) or managed (cropland, orchards, greenhouses), is challenged by a plethora of biotic agents including pathogens and pests. In its broadest sense the term 'biosecurity' encompasses the full range of such threats and our efforts to minimize, mitigate and recover from them. However, two areas of significant biosecurity concern have recently become the focus of targeted educational efforts for a variety of audiences, including graduate curricula. These include (1) threats caused by the inadvertent introduction, into a new location, of exotic pathogens and pests as a result of trade,

importation and transport, extreme weather events, and other means, and (2) the threat of deliberate introduction of pathogens or pests by individuals, groups or states for the purpose of causing harm to food production, trade and commerce, the environment, social stability, or other targets. Several graduate plant pathology curricula in the United States (e.g., Oklahoma State University, Pennsylvania State University, Rutgers University) and elsewhere (e.g., Murdoch University, University of New England) now include coursework specifically addressing plant biosecurity. Extra-curricular courses, hosted by universities or government agencies, or developed as an educational component of integrated grant award, are becoming more common. Notably, Kansas State University offers a week-long summer course on these topics for both graduate students and professionals from around the globe (https://www.bri.k-state.edu/news/events.html).

Essential professional training

The responsibility of scientific professionals extends beyond our individual activities and behavior to include the professional education and training of our students and mentees. Although graduate student mentors vary widely in their attention and diligence in guiding their students through both scientific and professional learning and experiences it is fair to say that the vast majority would agree that training in these skills and abilities should be part of the graduate experience. One example of how this can be approached is by offering a graduate class such as 'Career Skills and Professionalism for Graduate Students in Science,' now taught at Oklahoma State University (similar courses are offered at a few other U.S. plant pathology graduate programs), in which biological and professional ethics are recurring themes in addressing a variety of career issues as job-seeking and interviewing, scientific writing, mentoring, effective teaching, "people skills" and the practice of science. Some of these themes are touched on in more detail below.

- **Ethics.** Scientific professionals frequently encounter dilemmas and choices in both professional and scientific ethics. On one hand, as professionals, we must recognize that agriculture is a vast and complex international system that impacts virtually every person on the planet. Ethical considerations related to the production of food, feed and fiber are as diverse as the production systems, environments and stakeholders involved. Where can solutions – or at least acceptable balances – be found to manage the challenges we face today as well as those of tomorrow? Clearly, these issues cannot be resolved by the efforts of one or even a few, and new dilemmas will emerge as agricultural practices continue to evolve and the world continues to change. At the national level, each country must acknowledge that the Earth is a shared resource on which we all depend for food, fiber, and shelter. Actions of any nation that impact the natural environment are felt by all. Developed nations having substantial resources and modern technology will need to work hand in hand with developing nations whose food security and environmental stability are at greater risk. On the other hand, we make scientific ethical choices constantly as we design, perform, evaluate and report experiments, findings, interpretations and conclusions. Our experience has taught us that we cannot give students a blueprint for how to behave in every situation they will face. Rather, we can make our expectations of ethical behavior clear, serve as strong role models and examples, and provide trainees with tools with which they can better make informed and balanced decisions. In the Oklahoma State University class in career skills (see above) faculty guide the students as they practice these tools via role-playing exercises and scenario-driven pathways. We hope that this training will have a "trickle-up" effect as these young scientists and future leaders make their careers in agriculture and the agricultural sciences.
- **Research skills**. Most plant pathology graduate students around the world learn research skills 'on the job' as they embark on their M.S. or Ph.D. research programs. Important elements of this degree component include how to formulate hypotheses and design robust experiments with appropriate controls to test them. Types of plant pathology research have been expanding to embrace new technologies and multidisciplinary approaches. Interdisciplinary research, for example the 'lab on a chip' concept in which engineering systems are applied to understand the physical force exerted by plant pathogens (Tayagui et al. 2017), or the increasing application of airborne multi-spectral sensors for surveillance of forests (Sandino et al. 2018) will likely continue to increase. Thus, future plant pathologists will also need a broad comprehension of the advances being made in other disciplines. The contemporary graduate student supervision committee often includes non-university scientists who are subject experts. The range of research training experiences available to graduate students is now a continuum from fully university (or postgraduate degree conferring institute)-based to working in a non-academic institute with an off-site academic supervisor. The latter example can be viewed as a long-term internship; in some instances this is where the student acquires some of the core practical skills including aseptic culturing, culture maintenance and stewardship, and field application, interacting directly with primary producers and other stakeholders.
- **Scientific writing.** Scientific documents are the 'currency' of science, the ultimate way to communicate the

results of scientific research to stakeholders, be they farmers, Extension educators, government agency personnel, policy-makers, or the public. The nature of the audience, the message to be conveyed, and the use to which the document will be applied necessitate different writing approaches and styles. Many new graduate students have had limited previous writing experience, and are unlikely to be familiar with the current, accepted "scientific writing" style. Thus, developing excellent writing skills is a critical element of graduate training. Opportunities to develop and practice writing skills abound in graduate programs as students write term papers, research reports, meeting abstracts and proceedings, and sometimes popular papers. However, universities differ widely in the mechanisms of *teaching* writing skills. In some cases it is left to the major professor, who may or may not themselves be skilled writers, while in other universities the graduate curriculum may include courses on scientific writing and critical thinking; or seminars, workshops or tutors may be available from university-wide writing centers. This critical professional skill should not be left to chance.

- **Teaching skills**. In a major sense, teaching is a form of communication to a particular audience and the ability to teach effectively will be a significant asset in almost any career. Students may go on to be effective college teachers in the fields of plant health, plant pathology and/or plant-microbe interactions, while others who enter extension outreach, governmental positions and agricultural businesses often find that teaching skills and experience are significant assets. Graduate students at many universities gain experience by teaching hands-on laboratory or topical discussion sections that are complementary to classroom lectures provided by a faculty member; these roles may be supported financially by a 'teaching assistantship' or may be a requirement for all students in a particular department as part of their training. This approach, adopted many years ago in the United States, is now widely applied also in Europe. Another option is for students to avail themselves of teaching workshops, short courses, printed instructional learning materials, and other teaching resources often provided by universities, and often available to graduate students as well as early-career and seasoned professors (for example, Oklahoma State University offers all of these resources at its Institute for Teaching and Learning Excellence; https://itle.okstate.edu).
- **Public communication and outreach to a variety of audiences**. The ability to communicate complex ideas (e.g., oral exam, thesis defense, scientific meeting) is critical to scientific discourse and to the development and sustaining of collaborations. Even more challenging is the communication of complex ideas to stakeholders (from primary producers to senior industry representatives). Further, contemporary communications styles (e.g., Twitter, the least comprehensible unit) and changing social interaction habits (e.g., the 'social expectation' of an instant response to an email) are dramatically reducing the ability of many students to effectively engage in scientific discussions; they may answer questions but struggle to place the answer into context and discuss an idea. This phenomenon is not limited to verbal communications but is apparent in written communications as well. The practice of minimum necessary characters has costs. Understanding who are the 'stakeholders' by whom our work in plant pathology is shaped, and to whom our outputs are targeted, is a critical concept for future graduates of plant pathology and related graduate study programs. The ability to engage stakeholders as research is planned and to communicate our findings to them within the context of their environment are crucial to the successful translation of newly generated scientific knowledge to effective applications in the field. Communicating with funding administrators and policy makers is equally important. Yet, effective communication with these audiences is rarely taught since communication skills in graduate programs almost always focus on scientific writing and oral (and to some extent visual) presentation to professional audiences. However, opportunities to gain experience in non-scientific communication abound, especially through student involvement in the Extension and outreach functions of many universities (in the United States, particularly the land grant universities), which involve face-to-face interactions with commodity groups, farmers, grade-school groups, local government representatives, science fair and agricultural fair attendees, and others. Faculty mentors, who may be protective of the time available for their graduate students to conduct laboratory research, should be encouraged to support opportunities that offer such non-traditional experiences to graduate students.
- **The art of developing productive collaborations**. Collaboration, which is an ever more integral part of scientific research (Greene 2007), continues to increase (Abramo et al. 2009), especially as multidisciplinary approaches to problem-solving become the norm. Collaboration, at both the domestic and international levels, can occur between research institutions, governments, industries and communities. It provides increased opportunities to generate data and knowledge, improved validity and credibility of research, extended applicability of research, and mutually beneficial relationships that can contribute to solving global challenges. Access to research funding may be improved, and increased visibility, expanded capacity, ability to share resources, risk management, prestige and credibility, and greater productivity are all identified as advantages of collaboration (https://ori.hhs.gov/education/products/niu_collabresearch/collabresearch/need/need.html; Lee and Bozeman 2005).

The Australian government, for example, places a strong emphasis on the importance of international collaboration (https://www.arc.gov.au/policies-strategies/strategy/international). Many do not realize that collaboration skills ("people skills") can be taught and practiced. Collaboration skills should be included in course structures (http://theconversation.com/ten-rules-for-successful-research-collaboration-53826).

- **Project management, 'people skills' and budget management**. Another often-overlooked area in the training of graduate students is understanding how to effectively manage projects, people and budgets. Early career professionals may find these business and human aspects of their jobs to be as, or even more, challenging than scientific ones. Research funders, as well as institutional policies and regulations, whether within or external to an organization, have increased the level of scrutiny applied to project management and utilization of funds. In many cases annual audits of accomplishments, milestone achievements, and reconciliation of expenditures are critical parts of a project report. While specific management training is generally not included in formal graduate curricula, short courses (e.g., https://doresearch.stanford.edu/training/research-administration/expenditure-statement-reconciliation-and-review) are provided by many institutions and research students in graduate programs should be encouraged to complete these as they begin their thesis research.
- **Intellectual property/patenting/paths to commercialization.** Understanding the need for protecting intellectual property (IP) as well as identifying and managing it are increasingly important for researchers, whether in academic institutions, government or industry. In some cases one can simply copyright research outcomes through publication, while in other cases patenting or trademarking may be the appropriate form of protection. The context of the research or the implications of its applications may affect what steps will be necessary. For example, variation in IP laws from country to country leads to greater complexity of IP protection within international collaborative projects. Researchers should know the relevant contact points within their institution for advice on achieving protection or avoiding conflict. Courses or training in IP are now offered at most universities, and these are recommended to plant pathology trainees (https://www.enago.com/academy/intellectual-property-rights-what-researchers-need-to-know/).

Teaching approaches, resources and tools

Today's scientific educators have a wide range of powerful tools in for teaching. Traditional textbooks are less frequently used and more (and often more up-to-date) materials are available online. By offering rapid access to information and images the internet is useful to both students and instructors (Schumann 2003). Of significant value for plant pathology training all over the world are the teaching materials provided by the American Phytopathological Society (https://www.apsnet.org/Pages/default.aspx), which are widely used by students proficient in the English language. Such material is extremely useful in developing countries. In some instances, entire courses are taught online; for example, online courses on phytopathology, nematology, entomology and virology are given in the Netherlands. Online learning, by offering a flexible learning process and the possibility to custom-design course content, is ideal for professionals, allowing them to study material at their own pace and place.

A vision for the future: Strong and effective graduate training in plant pathology

Plant pathology graduate training for the future must focus on several core elements: 1) The challenges posed by plant diseases to the production of food and fibre, and sustainability of natural environments will not decrease. In fact, as the world faces the ever-growing impact of climate change it is highly likely that the importance of plant health will continue to increase. 2) An interdisciplinary approach coupled with increased collaboration will continue to be the most effective research framework for the future. 3) Graduate training must embrace advancements achieved through the use of new technologies and methods. 4) Training must ensure that all students learn the fundamentals of plant pathology that enable the identification of a plant disease in the field. 5) We must address the objective of educating the next generation of phytopathology scientists and not technologists.

Compliance with ethical standards

Conflict of Interest The authors declare that they have no conflict of interest.

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