Article Manuscript

The Canadian Fungal Research Network: Current Challenges and Future Opportunities

Linda C. Horianopoulos[1]*, Emile Gluck-Thaler[2]*, Isabelle Benoit Gelber[3], Leah E. Cowen[4], Jennifer Geddes-McAlister[5], Christian R. Landry[6], Ilan S. Schwartz[7], James A. Scott[8], Adnane Sellam[9], Donald C. Sheppard[10], Toby Spribille[11], Rajagopal Subramaniam[12], Allison K. Walker[13], Steven D. Harris[14]^, Rebecca S. Shapiro[5]^, Aleeza C. Gerstein[15]^

*equal contributions, corresponding authors: horianol@msl.ubc.ca; egluckthaler@pitt.edu
^equal contributions

[1]Department of Microbiology and Immunology, University of British Columbia, Vancouver, Canada
[2]Department of Biological Sciences, University of Pittsburgh, Pittsburgh, USA
[3]CSFG, Department of Biology, Concordia University, Montreal, Canada
[4]Department of Molecular Genetics, University of Toronto, Toronto, Canada
[5]Department of Molecular and Cellular Biology, University of Guelph, Guelph, Canada
[6]Département de biologie and Département de biochimie, microbiologie et bio-informatique, Université Laval, Québec city, Canada
[7]Division of Infectious Diseases, Department of Medicine, Faculty of Medicine & Dentistry, University of Alberta, Edmonton, Canada
[8]Dalla Lana School of Public Health, University of Toronto, Toronto, Canada
[9]Department of Microbiology, Infectious Disease and Immunology, Montreal Heart Institute, Université de Montréal, Montréal, Canada
[10]Department of Microbiology and Immunology, McGill University; McGill Interdisciplinary Initiative in Infection and Immunity, Montréal, Canada
[11]Department of Biological Sciences, University of Alberta, Edmonton, Canada
[12]Agriculture and Agri-Foods Canada; Ottawa Research and Development Centre, Ottawa, Canada
[13]Department of Biology, Acadia University, Wolfville, Canada
[14]Department of Biological Sciences, University of Manitoba, Winnipeg, Canada
[15]Departments of Microbiology & Statistics, University of Manitoba, Winnipeg, Canada

ABSTRACT

Fungi critically impact the health and function of global ecosystems and economies. In Canada, fungal researchers often work within silos defined by sub-discipline and institutional type, complicating the collaborations necessary to understand the impacts fungi have on the environment, economy, and plant and animal health. Here, we announce the establishment of the Canadian Fungal Research Network (CanFunNet, https://fungalresearch.ca) whose mission is to strengthen and promote fungal research in Canada by facilitating dialogue among scientists. We summarize the challenges and opportunities for Canadian fungal research that were discussed at CanFunNet's inaugural meeting in 2019, and identify four priorities for our community: 1) increasing collaboration among scientists; 2) studying diversity in the context of ecological disturbance; 3) preserving culture collections in the absence of sustained funding; and 4) leveraging diverse expertise to attract trainees. We have gathered additional information to support our recommendations, including a survey identifying underrepresentation of fungal-related courses at Canadian universities, a list of Canadian fungaria and culture collections, and a case study of a human fungal pathogen outbreak. We anticipate that these discussions will help prioritize fungal research in Canada, and we welcome all researchers to join this nationwide effort to enhance knowledge dissemination and funding advocacy.

Keywords: Fungi; Mycology; Canada; Research; Community

INTRODUCTION

Fungal activities critically impact the functioning of Canadian society

Fungi comprise a morphologically, metabolically, and ecologically diverse kingdom estimated to include between 2 and 12 million species that, together, colonize virtually all known natural and manufactured habitats on the planet (Wu et al., 2019). Although fungi are often invisible to the human eye, their varied ecological activities have definitive and remarkable impacts on the functioning of global ecosystems and societies (Figure 1). In Canada, as everywhere, mutualistic fungi are key to forest health and crop agriculture, and play key biochemical roles in essential food and beverage production. They are also a major and highly visible component of forest and tundra ecosystems that cover more than 80% of Canada, and play a prominent role in the indigenous culture of First Nations. At the same time, fungi also represent serious threats to forest health and food security as pathogens that prematurely kill trees and negatively impact yields of all Canadian food crops (Gilbert & Tekauz, 2000). Especially troubling are increases in the frequency of human fungal infections: ~1.8% of the Canadian population (~650K people) are estimated to be currently affected by life-threatening fungal infections (Dufresne et al., 2017), and this number is expected to rise as a consequence of the continued increase in the number of at-risk elderly and immune-compromised individuals (Canada, 2012; Dufresne et al., 2017; Laupland et al., 2005; St-Germain et al., 2008). Together, these factors also highlight the major impact of fungi on the economy, both through effects on major contributors to the Canadian economy (e.g., forestry and agriculture), and the significant costs incurred in treating fungal infections (Wilson et al., 2002). In contrast, harnessing the extensive metabolic diversity of fungi could have positive economic, ecological, and health impacts for Canada. Overall, these facts highlight the importance of conducting fungal research in Canada in a thoughtful and concerted manner.

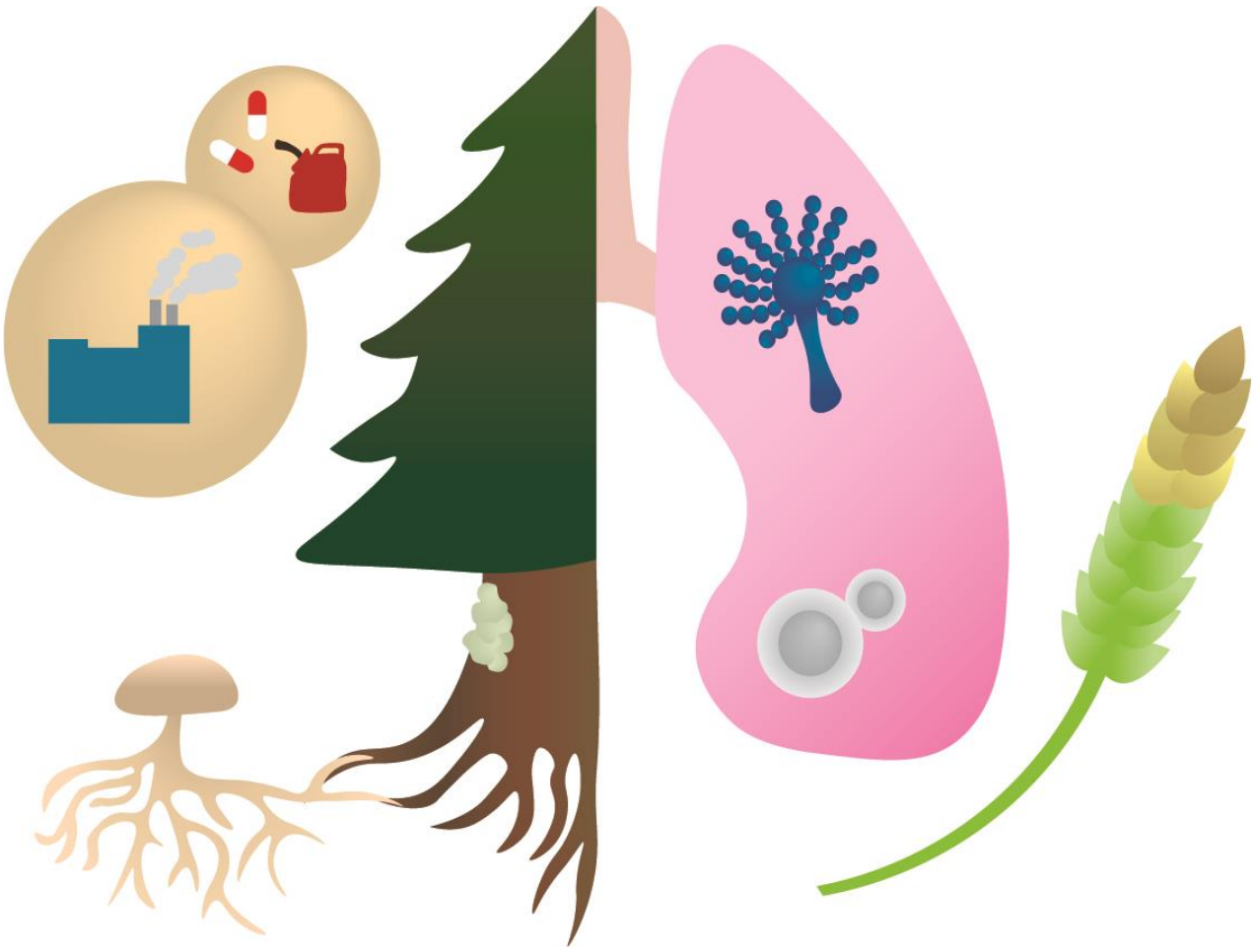

Figure 1: The varied activities of fungi are of broad economic, environmental, medical, and agricultural relevance in Canada. These activities are both positive (e.g., the fungal underpinnings of forest health, biotechnology and pharmaceuticals) and negative (e.g., adverse effects on human and plant health).

The establishment of the Canadian Fungal Research Network for strengthening fungal science in Canada

Managing the cross-sectional impacts of fungi on public health, the environment, and agriculture requires an interdisciplinary approach. Yet fungal researchers are often embedded in separate sub-disciplines, such as forestry, microbiology, botany, or genetics, which may not be conducive to the collaboration necessary to address these problems. In order to remedy what is largely an artificial constraint, here we announce the establishment of the Canadian Fungal Research Network (CanFunNet, https://fungalresearch.ca) whose aim is to support the exchange of technical and theoretical expertise among fungal scientists from different research sectors, and to enhance training opportunities for the next generation of Canadian mycologists. To initiate the establishment of the CanFunNet, we, the authors, met in Winnipeg in October 2019 to discuss strengths and weaknesses of the Canadian mycology community as well as opportunities for advancement, which we discuss herein. While not all interested members of the community were able to attend this meeting, we welcome and encourage all researchers to join and contribute to the CanFunNet in order to enhance research productivity and impact, and to catalyze greater funding opportunities for the community as a whole.

THE FUNGAL RESEARCH COMMUNITY

Diverse expertise in fungal biology exists across Canada

Fungal research in Canada spans the diversity of the fungal kingdom. While typically underrepresented in individual institutions compared with plant, animal, and bacterial biologists, many Canadian universities, medical schools, and government agencies have at least one scientist or faculty member engaged in some aspect of fungal research. Through discussions with CanFunNet members, it became clear that researchers not only focus on diverse species, but also employ a variety of techniques ranging from classical forward and reverse genetics to post-genomic tools. Model fungi such as *Saccharomyces cerevisiae* are used to study fundamental aspects of cell biology and evolution, while other fungi of biotechnological relevance are characterized with the goal of producing beneficial enzymes and metabolites for food, natural resource, and pharmaceutical industries. The ecological roles of environmental fungi ranging from lichens to saprotrophs to plant mutualists, are subject to intense investigation, particularly within the context of climate change. The genetics and biology of human and plant pathogenic fungi are studied in detail with the ultimate objective of improving patient outcomes and crop yields. A major strength of this diversity is that it is rare to find research groups working on the same topics. This means that direct competition among research groups is rare, yet the collaborative potential for interdisciplinary research within Canada is not yet fully realized.

Promoting communication and collaboration across fungal disciplines

The dispersion of fungal researchers across Canadian institutions, and lack of a critical mass at any single centre, makes building productive research partnerships among fungal scientists a challenge. A common concern expressed at the CanFunNet meeting by researchers from distinct sub-disciplines (e.g., clinical mycology, fungal pathogenesis, fungal ecology and evolution) was that they feel like minorities within their fields at large (e.g., clinical microbiology, microbial

pathogenesis, ecology and evolution). Furthermore, it is common for researchers to focus on their organism of interest, and to seek local collaboration. Given that the number of fungal experts is small, constructive collaboration will need to transcend distance as well as specific organisms and methodologies.

Through discussions at the CanFunNet meeting, it became apparent that despite the diversity of research interests, similar techniques in genetics, transcriptomics, proteomics, metabolomics, molecular biology, and bioinformatics are being employed across the country to interrogate fungal biology, ecology, and evolution. As an example for how increased communication among fungal scientists will help improve research activities, several researchers at the CanFunNet meeting made note that many cutting-edge protocols must be modified in order to be used for fungi. With the help of existing resources (e.g., FungiDB, PRIDE Xchange Consortium), CanFunNet will help facilitate communication necessary to share protocols and datasets, with the goal of making more rapid progress in developing fungal-specific protocols.

A second challenge to fostering collaborations within the fungal research community is the cost associated with travel to meetings and conferences both nationally and abroad. For example, while several conferences held in the United States are highly relevant for fungal biologists (e.g., the Annual Meeting of the Mycological Society of America, the Genetics Society of America's Fungal Genetics Meeting, and the Gordon Research Conference on Cellular and Molecular Fungal Biology), the cost of attending these meetings is often prohibitive for Canadian researchers, especially students. Existing annual Canadian meetings such as those of the Canadian Society of Microbiologists, the Canadian Phytopathological Society, the Canadian Botanical Association, and the Canadian Society for Ecology and Evolution draw some fungal researchers, but these meetings are broad in scope and do not attract the necessary critical mass for networking and fostering collaboration across the fungal research community in Canada.

Funding challenges and opportunities

Over the past ten years, the Canadian Institutes for Health Research (CIHR) has invested ~$50 million into fungal research at all levels. However, proposals including the keyword "fungi" represent only 0.9% of total funding allocated to project grants. By comparison, ~$500 million in total funding and 2.4% of project funding is directed to projects with the keyword "bacteria", even though the global importance of fungi is comparable to that of bacteria. Scientists attending the CanFunNet meeting discussed two strategies for remedying this discrepancy in support across funding agencies: 1) strengthening ties among Canadian fungal researchers to increase funding advocacy and research visibility, and 2) leveraging diverse research expertise to enhance collaborative grant support. Beyond increasing advocacy and collaboration, persistent challenges remain to closing the funding gap. For example, it is difficult for fungal researchers to meet the recommendations of CIHR and Natural Sciences and Engineering Research Council of Canada (NSERC) grant applications for seeking out Canadian reviewers familiar with their proposed system, given the relatively small list of qualified reviewers.

At the national level, one positive development towards closing the funding gap through increasing the profile of fungal research at large is a new (2019) Canadian Institute for Advanced Research (CIFAR) program focused on the Fungal Kingdom: Threats & Opportunities

(https://www.cifar.ca/research/program/fungal-kingdom). This program brings leading scientists from around the world to Canada to discuss the major threats and opportunities in this research area, and to communicate their importance to government representatives and funding agencies. At the local level, regional meetings, such as the annual Great Lakes Mycology Meeting, the newly established Atlantic Canada Mycology Meeting, and the soon-to-be reestablished Montreal Yeast Meeting, offer excellent opportunities to increase visibility of Canadian fungal research, and provide important networking opportunities for scientists, especially trainees and early career researchers.

Outlook: Prioritizing cohesion among Canadian fungal researchers

Overall, discussions at the CanFunNet meeting concerning the state of Canadian fungal research community were hopeful, encouraging, and solution-oriented. Participants discussed two potential strategies to address what were identified as the most immediate threats to the future of Canadian fungal research: institutional siloing and a funding gap. First, regional communities and collaborations should be strengthened by increasing support for regional and national meetings. For example, while regional mycological meetings exist in Eastern Canada (e.g., the annual Great Lakes and Atlantic Canada Mycology Meetings), similar meetings are lacking in Western Canada and should be established. While there was little support at the meeting for establishing a new scientific society with its own annual meetings, participants were generally enthusiastic about hosting fungal-specific pre-meetings/workshops at existing conferences such as the Canadian Society of Microbiologists, or establishing a Canadian chapter of the Mycological Society of America in order to help promote networking within the Canadian mycological community.

Second, more resources should be developed for improving communication among Canadian fungal researchers, especially those not able to attend meetings. Several participants at CanFunNet noted that simply attending more meetings is not a feasible solution for everyone. There was particular support to generate a searchable database of Canadian researchers working on fungi that would include specialties, techniques used, and contact information. We foresee that this would make collaboration easier and enhance the ability of researchers to secure grant funding. In summary, Canada has a dedicated community of researchers working hard to advance mycological research in diverse sub-disciplines. However, there is a need for improved communication, collaboration, and cohesion amongst mycologists across all levels and research areas. The development of increased professional ties within the community has the potential to increase public awareness, student interest, and funding for fungal research.

ASSESSMENT OF FUNGAL DIVERSITY

Canada's varied geographic and geological zones may harbour new mycodiversity

As the primary decomposers of plant materials, fungi are responsible for recycling nutrients across trophic levels; as mutualists, they shape the diversity and functioning of above- and below-ground communities; as life-threatening pathogens of plants and animals, they consume crops at our expense and represent emerging infectious diseases of great concern (Fisher et al., 2020). The varied climates, soils, and forests found across Canada suggest that our country is an important reservoir of global fungal biodiversity. Unlike plants and animals, the diversity of several fungal

groups increases with distance from the equator, peaking in temperate and boreal climates such as those found in Canada (Amend et al., 2010; Tedersoo et al., 2014). Yet despite their importance, we know little about the diversity of fungi that surround us in Canada, and the consequences of disrupting and modifying this diversity through anthropogenic activity.

Cost to access remote sites limits strain sampling and collection of metadata

The geographic immensity of Canada presents a challenge for cataloguing and studying its native mycoflora as much of Canada is remote and difficult to access. Furthermore, the isolation of fungi from plants, waters, and soils requires the rapid processing of samples under sterile conditions, which can be difficult to achieve without specialized infrastructure. Environmental conditions at remote sites, including weather and soil characteristics, are also difficult to measure, limiting the quality and quantity of ecological metadata that can be ascribed to isolated strains. These difficulties contribute to the lack of comprehensive assessments of Canadian fungal biodiversity to date, as well as a lack of understanding of environmental factors driving differences in fungal diversity across Canadian regions. For these reasons, catalogued cultures likely represent only a fraction of the diversity from a limited portion of geographic regions across Canada.

Environmental change is occurring rapidly, and the window for establishing baseline assessments of diversity may be closing quickly

Assessments of diversity are critical for prioritizing regions for conservation and for sustainably managing natural resources and ecosystems. However, one of the more insidious consequences of global climate change is that remote environments may be irreversibly disrupted before their baseline levels of diversity have been assessed. Without pre-disruption assessments of diversity, managing the recovery of these ecosystems becomes challenging or impossible, as there is no standard with which to assess the effectiveness of recovery efforts. The impacts of global climate change and other anthropogenic activities on the structure and function of fungal communities in Canada is not currently known, making it difficult to predict their effects on future landscapes.

Dedicated observation sites to assess the impacts of climate change on fungal diversity across ecosystems

Although the difficulties in monitoring fungal diversity across Canada have been highlighted, there exists an opportunity to establish observation sites in ecologically diverse places across Canada to represent distinct ecological niches to monitor fungal diversity and environmental metadata over time. This will provide the missing baselines and knowledge of how fungi respond to climate change and other anthropogenic activities. Ultimately, this research would make Canada a leader in understanding the impacts of ecological disruptions within forest and freshwater ecosystems on a global scale. It will also improve the accuracy of models predicting the outcomes of possible interventions and restorations within these ecosystems and allow for continuous monitoring of emerging or expanding fungal pathogens, which pose a risk to crop and human health.

Another avenue to monitor fungal diversity in Canada is through engaging the public in documenting fungal diversity. Macrofungi, such as lichen- and mushroom-forming fungi, are amenable to collection and identification with little need for specialized equipment. Established

citizen science programs, such as the North American Mycoflora project which collects, documents, preserves and sequences of macrofungi across North America, represent a fantastic opportunity for engaging both amateur and professional Canadian mycologists to document Canadian fungal diversity within an established framework (http://mycoflora.org/). However, only 10 of the 150 regional Mycoflora projects are currently based in Canada. Increased support and outreach activities to help everyone participate in such initiatives would represent a significant step towards cataloguing local mycodiversity within Canada.

FUNGAL CULTURE COLLECTIONS

Significant repositories and resources of Canadian fungal biodiversity exist

Culture collection biobanks are common resources that facilitate the reproducibility of science, and support continued access to critical biological resources; and Canada is home to several important fungal biobanks and fungaria (See Box 1). The Canadian Collection of Fungal Cultures (DAOMC/CCFC), directed by Agriculture and Agri-food Canada (AAFC), preserves a live culture collection of primarily agriculturally important fungi including ~ 20,000 living fungal cultures representing > 4,000 species (Sigler, 2004). The UAMH Centre for Global Microfungal Biodiversity (https://www.uamh.ca/), now housed at the University of Toronto, Dalla Lana School of Public Health contains over 12,000 living biospecimens representing over 3,200 taxa, and includes many type strains and isolates of medical, veterinary, and environmental relevance collected over nearly 90 years. UAMH also provides research support and training in order to serve the community and support their operating costs. Several smaller Several Canadian fungaria with dried specimens are searchable online via MycoPortal (mycoportal.org), including ACAD (Acadia University), NBM (New Brunswick Museum), FNL (Foray Newfoundland and Labrador Fungarium), and BMSC (Bamfield Marine Science Centre). Each biobank has a distinct focus in terms of the types of fungi they collect, and while some overlap exists between repositories, they primarily house unique biological materials, including many specimens from Canada.

Non-government collections lack stable and predictable funding

There has been a downward trend in the financial support for culture collections globally, especially living culture collections. A lack of predictable funding to ensure the stability of collections over time is particularly a threat in Canada as funding was historically available through the now-defunct NSERC Major Resources Support program. For non-governmental collections such as the UAMH, funding is almost entirely dependent on strain sales. The availability of space to store fungal culture collections is also precarious, and operating costs are high as materials must be kept alive often requiring freezing and regular propagation. A previous perspective paper identified several of the Canadian culture collections as being vulnerable at the point of the retirement of their curators, and highlighted that collections may be lost as there is no accountability to ensure trusteeship of collections or to provide funding to transfer orphaned collections (Sigler, 2004). Propositions to overcome these challenges by transferring materials to more well established, global repositories are also problematic as transferring pathogens across borders can present legal and logistical problems, and would delay progress and accessibility of the strains. Therefore, funding for stable culture collections in Canada must be a priority for advocacy.

Accessing clinically relevant samples can be challenging

A concern voiced during the CanFunNet establishment meeting was the difficulty in accessing fungal clinical isolates. Acquiring clinical isolates faces distinct challenges as there are potential legal and patient privacy concerns between the provincial health authorities and the federal agencies that house collections regarding the ownership status of these strains, as well as safety concerns over the distribution of outbreak-associated isolates that may be multi-drug resistant. Currently, provincial and federal public health labs are not resourced as repositories; however, they accommodate requests from researchers as much as possible. With respect to fungi, the National Microbiology Laboratory (NML), run by the Public Health Agency of Canada, interfaces with provincial health authorities, and has recently increased its capacity for identification and analysis of clinical fungal isolates (Marek et al., 2019). However, since it is not a repository, there may be impediments to access strains, which slows or even halts important research taking place outside of government labs. Maintaining a culture repository in conjunction with health labs would provide more access for researchers, and provide documentation as to where clinically relevant strains have been sent.

Collections can enhance medical, agricultural, and environmental research

The immense biological diversity housed in Canadian fungal culture collections stands to support and promote initiatives of immediate relevance to public health, environmental health, and industry innovations. Agricultural and clinical isolates have been and will be instrumental for identifying mechanisms of disease resistance and monitoring disease outbreaks in Canadian fields and hospitals (see Box 2). Environmental isolates can be leveraged for bioprospecting of new medicines and the development of clean energy technologies.

The successful application of Canadian culture collections to next-generation research, especially in the age of genomics, will only improve as the visibility of these collections increases. Currently, only the UAMH collection can be searched online, however a recent major treasury board investment to mobilize biodiversity data in the AAFC collections means digitization and searchable online access is underway for the DAOMC/CCFC collection as well. The additional difficulties regarding access to clinical samples also need to be resolved in order to ensure research progress on medically important strains. Increased communication between government research scientists and clinicians is necessary to ensure that strains are distributed and acquired in a timely manner. In addition, advocacy for the reinstatement of Tri-Council agency support for biological resources such as culture collections must be a high priority for Canadian mycologists, to ensure that these resources are not lost.

TRAINING FUNGAL SCIENTISTS

Training opportunities: from far and wide, with room to grow

There is a considerable lack of fungal-focused undergraduate-level courses in Canada. In a survey we conducted of the 64 Canadian universities that offer a B.Sc. degree (data available at DOI: 10.6084/m9.figshare.12268334), fewer than half offer at least a single course focusing on some scientific aspect of fungi (Figure 2; median = 0, range = 0-4). By comparison, all but two

universities offer at least one course focusing on plants (Figure 2; median = 5, range = 0-32). At the 29 universities that offer both types of courses, an average of 7.5 times more plant courses are available for students to take. This discrepancy in courses directly impacts course content, with most fungal courses restricted to broad surveys of fungal science or merely a mention of fungi as part of a microbiology or general biology course, while many plant courses focus on specific aspects of plant science such as physiology, cellular biology, and community ecology. Differences in educational resources between plants and fungi notwithstanding, one positive finding of our survey is that at least one university-level fungal course is offered in nine of the ten Canadian provinces. This underscores the relevance of fungi to not just a single region of Canada, but to the country as a whole, and provides a rudimentary framework for expanding and growing educational resources that are available.

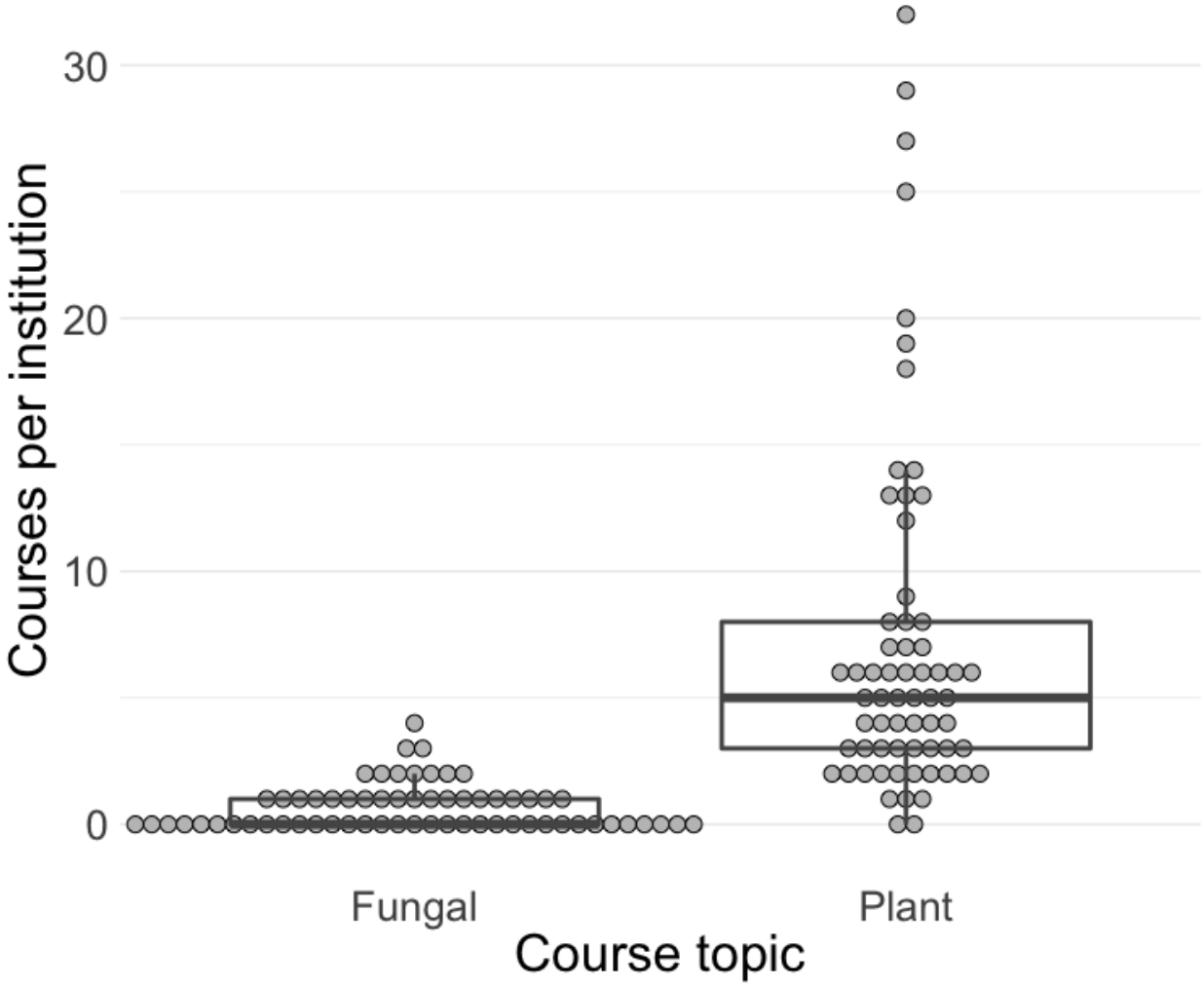

Figure 2: The distribution of plant and fungal courses offered at Canadian Universities. All 64 Canadian Universities offering a B.Sc. were surveyed for the number of active courses listed in the past two years whose titles contained keywords related to either plants ("plant", "botany", "flora") or fungi (“fungal”, "fungi", "mold", "lichen", "mushroom", "yeast", "mycology"). Each dot represents the number of courses offered per institution, and box-and-whisker plots summarizing each course type’s distribution are overlaid.

At the CanFunNet meeting, participants recognized that a collective effort to partially standardize curricular content related to mycology, and to increase the number of courses offered would have benefits for increasing student interest in fungi and attracting more graduate students into labs focused on fungal research. To this effect, increased coordination and cohesion between instructors teaching fungal biology should be prioritized, as they are likely to facilitate an increase in the number and quality of fungal courses that are available, especially in universities that currently lack them. For example, efforts could be made to standardize course materials through the use of common course learning outcomes, as well as provide a platform for sharing materials such as images, slides, or even videos of recorded lectures. Efforts could also be made to diversify the types of courses in which fungal content is presented. For example, medical programs offer a potential pathway to pique interest of microbiologists and infectious disease trainees towards careers in clinical mycology.

Formal training programs for budding young mycologists

Beyond undergraduate-level courses, early career fungal researchers in theory have access to educational resources outside of Canada. For example, there are several excellent workshops and training courses offered internationally that focus on mycology, such as the "Molecular Mycology: Current Approaches to Fungal Pathogenesis" course at the Marine Biological Laboratory in Woods Hole, MA, which provides lectures and hands-on instruction pertaining to human fungal pathogens, and the Yeast Genetics & Genomics Course at Cold Spring Harbor Laboratory, which centers around *S. cerevisiae*. However, there was a general consensus among the CanFunNet meeting participants that we should not rely on these courses for training Canadian students because of their high costs, limited enrollment, and increasing visa restrictions.

There was considerable discussion at the meeting for how to provide Canadian trainees with better training opportunities. The general consensus was that rather than replicating existing courses, we should take the opportunity to create a new resource that builds on the strength and expertise of Canadian researchers, to serve our trainees and attract trainees from other countries. There was a particular interest in developing a program focusing on genomics and computational biology, as these skills are increasingly in demand for conducting fungal research. CIFAR representatives in attendance at the CanFunNet promoted exploring the possibility of facilitating a pilot workshop in conjunction with a CIFAR Fungal Kingdom: Threats & Opportunities program meeting. As CIFAR has already assembled top-level researchers in these areas, there would be synergy in terms of logistics and resources, and this would advance the mutual goal of promoting and advocating for fungal research. A pilot workshop would also enable collection of information on course content and logistics. Meeting attendees expressed strong support for proceeding with the proposed workshop.

Loss of trainees to other countries

Through discussions at the CanFunNet meeting, it became apparent that Canada has no institutes that focus specifically on fungal science. Fungal research clusters exist in many other countries such as the United States (e.g., the Joint Genome Institute's Fungal Program, the University of Georgia's Fungal Biology Group), Scotland (the Aberdeen Fungal Group), The Netherlands (the Westerdijk Fungal Biodiversity Institute), Germany (the Leibniz Institute for Natural Product

Research and Infection Biology), and England (e.g., Manchester Fungal Infection Group). These multi-lab groups are typically well-funded, share resources and expertise, and tend to focus on one species or sub-discipline. Participants raised concern about the loss of Canadian trainees, especially post-doctoral researchers, to these and other fungal research groups outside of Canada (although to some extent, this reflects the general lack of robust funding for post-doctoral researchers in Canada). Nevertheless, strengthening the fungal research community in Canada should provide more attractive opportunities that allow us to retain trainees and promote their professional development. The excellent research and collaborative opportunities available in Canada would help to retain high calibre trainees in fungal research**.** In these ways, we can maintain and expand the fungal research community in Canada for the future.

Outlook: Opportunities for growth and retention of trainees

The strengths in our fungal research community can help attract trainees to Canada. At the individual lab level, there are diverse training opportunities and experienced mentors. Further, given the broad interest in creating a national mycology training course, this could further augment the opportunity for trainees in Canada to get mycology specific training. Such a course would also increase the visibility of Canadian fungal science and of Canadian fungal researchers to international trainees, which is essential for encouraging their participation and contribution to our community. Coupled with improved cohesion in university-level educational resources, such initiatives stand to increase the pool of early career fungal researchers, enhance the training experience for Canadians, attract international trainees, and improve the outlook for Canadian mycology research.

The future of Canadian Fungal Research: strength in networks

Canadian fungal research is flourishing, but there is room for growth and a need to preserve existing strengths. From our discussions at the CanFunNet establishment meeting, the key priorities are to strengthen the Canadian fungal research community, ensure opportunities for trainees, advocate for the preservation of culture collections, and broaden our understanding of the diversity of fungi that inhabit Canadian ecosystems. We envision a central role for CanFunNet in achieving these priorities by providing a platform to enable communication and advocacy on behalf of fungal scientists. This will maximize our capacity to address fundamental questions related to the health of Canadians, threats to the environment, and opportunities for economic growth in Canada. We recognize that not all interested fungal researchers in Canada were able to attend this meeting and contribute to this manuscript; however we welcome and encourage all interested researchers to contact us through the CanFunNet website (https://www.fungalresearch.ca/).

Box 1: Fungal diversity and the role of Canadian fungaria

Mycologists have documented the fungal diversity of Canada for over 200 years. More than one million curated specimens of fungi, including about a quarter million lichen specimens, are housed in Canadian fungaria, with the largest collections at the Royal Ontario Museum Fungarium (TRTC, 500,000 specimens), the Canadian National Mycological Herbarium (DAOM, 350,000), The University of British Columbia (approximately 100,000), and The University of Toronto (UAMH,

approximately 12,000 specimens of public health relevance). Nearly every province houses a large research collection and many universities maintain teaching collections, but almost no collection in Canada is currently maintained by a full-time curator. The collections support teaching as well as research in biodiversity, ecology, systematics and molecular evolution, not only in Canada, but more widely around the world.

Box 2: *Cryptococcus gattii* and the case for curating Canadian fungi

The Vancouver Island outbreak of *Cryptococcus gattii* is one of Canada's most infamous fungal epidemics. This outbreak represented an acute public health crisis because immunocompetent individuals were being infected whereas, typically, most systemic fungal infections affect the immunocompromised. The outbreak was also of considerable interest to the research community because *C. gattii* is traditionally found in tropical and subtropical climates, whereas Vancouver Island has a temperate climate. Furthermore, the incidence of *C. gattii* infections were higher during this outbreak than reported incidences in areas, such as Australia, where *C. gattii* is endemic (Kidd et al., 2004). At the time of the outbreak, the British Columbia Centre for Disease Control (BCCDC) collected clinical isolates from patients and Dr. Karen Bartlett collected environmental isolates. Many of these isolates were subsequently sent out by Dr. James Kronstad to mycologists worldwide, which facilitated rapid progress on understanding the source of infectious propagules, the diversity of genotypes, and the relationships between clinical and environmental isolates (Byrnes et al., 2009; Fraser et al., 2005; Ma et al., 2009; Ma & May, 2010; Ngamskulrungroj et al., 2011).

Recent predictions suggest that more fungal pathogens will emerge in Canada as the climate warms, including fungi not historically found in Canada (Casadevall et al., 2019; Garcia-Solache & Casadevall, 2010; Greer et al., 2008). In these events, there may be less global interest especially if the pathogen is not hypervirulent, but rather simply new to Canada. In this event, we must ask ourselves how Canadian mycologists are equipped to deal with such a situation. Fortunately, there is now a mycology group within the NML (established to deal with the emerging pathogen *Candida auris*). However, since the NML does not operate a publically accessible culture fungal collection, we believe that stable funding of repositories which interface with NML or the establishment of a clinically focused repository within NML may be necessary to launch an effective response to public health concerns by Canadian mycologists.

Acknowledgements

The authors thank Amrita Bharat, who participated at the establishment meeting and provided helpful comments on the manuscript. The CanFunNet establishment meeting was supported by the University of Manitoba and a Planning and Dissemination Grant from the Canadian Institutes of Health Research (CIHR).

References

Amend, A. S., Seifert, K. A., Samson, R., and Bruns, T. D. 2010. Indoor fungal composition is geographically patterned and more diverse in temperate zones than in the tropics. PNAS. 107(31): 13748–13753. doi: 10.1073/pnas.1000454107. PMID: 20616017.

Byrnes, E. J., 3rd, Bildfell, R. J., Frank, S. A., Mitchell, T. G., Marr, K. A., and Heitman, J. 2009. Molecular evidence that the range of the Vancouver Island outbreak of Cryptococcus gattii infection has expanded into the Pacific Northwest in the United States. J. Infect. Dis. 199(7), 1081–1086. doi: 10.1086/597306. PMID: 19220140.

Casadevall, A., Kontoyiannis, D. P., and Robert, V. 2019. On the Emergence of Candida auris: Climate Change, Azoles, Swamps, and Birds. mBio. 10(4). https://doi.org/10.1128/mBio.01397-19. PMID: 31337723.

Dufresne, S. F., Cole, D. C., Denning, D. W., and Sheppard, D. C. 2017. Serious fungal infections in Canada. Eur. J. Clin. Microbiol. Infect. Dis. 36(6): 987–992. doi: 10.1007/s10096-017-2922-y. PMID: 28161745.

Fisher, M. C., Gurr, S. J., Cuomo, C. A., Blehert, D. S., Jin, H., Stukenbrock, E. H., Stajich, J. E., Kahmann, R., Boone, C., Denning, D. W., Gow, N. A. R., Klein, B. S., Kronstad, J. W., Sheppard, D. C., Taylor, J. W., Wright, G. D., Heitman, J., Casadevall, A., and Cowen, L. E. 2020. Threats Posed by the Fungal Kingdom to Humans, Wildlife, and Agriculture. mBio. 11(3). https://doi.org/10.1128/mBio.00449-20. PMID: 3237159.

Fraser, J. A., Giles, S. S., Wenink, E. C., Geunes-Boyer, S. G., Wright, J. R., Diezmann, S., Allen, A., Stajich, J. E., Dietrich, F. S., Perfect, J. R., and Heitman, J. 2005. Same-sex mating and the origin of the Vancouver Island Cryptococcus gattii outbreak. Nature. 437(7063): 1360–1364. doi: 10.1038/nature04220. PMID: 16222245.

Garcia-Solache, M. A., and Casadevall, A. 2010. Global warming will bring new fungal diseases for mammals. mBio. 1(1). https://doi.org/ 10.1128/mBio.00061-10. PMID: 20689745.

Gilbert, J., and Tekauz, A. 2000. Review: Recent developments in research on fusarium head blight of wheat in Canada. Can. J. of Plant Pathol. 22(1): 1–8. doi: 10.1080/07060660009501155.

Greer, A., Ng, V., and Fisman, D. 2008. Climate change and infectious diseases in North America: the road ahead. CMAJ. 178(6): 715–722. doi: 10.1503/cmaj.081325. PMID: 18332386.

Kidd, S. E., Hagen, F., Tscharke, R. L., Huynh, M., Bartlett, K. H., Fyfe, M., Macdougall, L., Boekhout, T., Kwon-Chung, K. J., and Meyer, W. 2004. A rare genotype of Cryptococcus gattii caused the cryptococcosis outbreak on Vancouver Island (British Columbia, Canada). PNAS. 101(49): 17258–17263. doi: 10.1073/pnas.0402981101. PMID: 15572442.

Laupland, K. B., Gregson, D. B., Church, D. L., Ross, T., and Elsayed, S. 2005. Invasive Candida species infections: a 5 year population-based assessment. J. Antimicrob. Chemother. 56(3): 532–537. doi: 10.1093/jac/dki258. PMID: 16040623.

Ma, H., Hagen, F., Stekel, D. J., Johnston, S. A., Sionov, E., Falk, R., Polacheck, I., Boekhout, T., and May, R. C. 2009. The fatal fungal outbreak on Vancouver Island is characterized by enhanced intracellular parasitism driven by mitochondrial regulation. PNAS. 106(31): 12980–12985. doi: 10.1073/pnas.0902963106. PMID: 19651610.

Ma, H., and May, R. C. 2010. Mitochondria and the regulation of hypervirulence in the fatal fungal outbreak on Vancouver Island. Virulence. 1(3): 197–201. https://doi.org/10.4161/viru.1.3.11053. PMID: 21178442.

Marek, C., Croxen, M. A., Dingle, T. C., Bharat, A., Schwartz, I. S., Wiens, R., and Smith, S. 2019. The use of genome sequencing to investigate an outbreak of hospital-acquired mucormycosis in transplant patients. Transpl. Infect. Dis. 21(5): e13163. doi: 10.1111/tid.13163. PMID: 31472083.

Ngamskulrungroj, P., Price, J., Sorrell, T., Perfect, J. R., and Meyer, W. 2011. Cryptococcus gattii virulence composite: candidate genes revealed by microarray analysis of high and less virulent Vancouver island outbreak strains. PloS One. 6(1): e16076. doi: 10.1371/journal.pone.0016076. PMID: 21249145.

Pfaller, M. A., and Diekema, D. J. 2007. Epidemiology of invasive candidiasis: a persistent public health problem. Clin. Microbiol. Rev. 20(1): 133–163. doi: 10.1128/CMR.00029-06. PMID: 17223626.

Sigler, L. 2004. Culture collections in Canada: perspectives and problems. Can. J. Plant Pathol. 26(1): 39–47. doi: 10.1080/07060660409507110.

St-Germain, G., Laverdière, M., Pelletier, R., René, P., Bourgault, A.-M., Lemieux, C., and Libman, M. 2008. Epidemiology and antifungal susceptibility of bloodstream Candida isolates in Quebec: Report on 453 cases between 2003 and 2005. Can. J. Infect. Dis. Med. Microbiol. 19(1): 55–62. doi: 10.1155/2008/634046. PMID: 19145263.

Tedersoo, L., Bahram, M., Põlme, S., Kõljalg, U., Yorou, N. S., Wijesundera, R., Villarreal Ruiz, L., Vasco-Palacios, A. M., Thu, P. Q., Suija, A., Smith, M. E., Sharp, C., Saluveer, E., Saitta, A., Rosas, M., Riit, T., Ratkowsky, D., Pritsch, K., Põldmaa, K., et al. 2014. Fungal biogeography. Global diversity and geography of soil fungi. Science. 346(6213): 1256688. doi: 10.1126/science.1256688. PMID: 25430773.

Wilson, L. S., Reyes, C. M., Stolpman, M., Speckman, J., Allen, K., and Beney, J. 2002. The direct cost and incidence of systemic fungal infections. Value Health. 5(1): 26–34. doi: 10.1046/j.1524-4733.2002.51108.x PMID: 11873380.

Wu, B., Hussain, M., Zhang, W., Stadler, M., Liu, X., and Xiang, M. 2019. Current insights into fungal species diversity and perspective on naming the environmental DNA sequences of fungi. Mycology. 10(3): 127–140. doi: 10.1080/21501203.2019.1614106. PMID: 31448147.