Charting a Future for Emerging Infectious Disease Modelling in Canada

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IN RECOGNITION

We acknowledge that Indigenous peoples are the traditional guardians of this land that we call Canada in which we gather.

We acknowledge the historical oppression of lands, cultures and the original Peoples of this country and know we have a role to play in the path to decolonization that we share together.

We recognize our duty to fight for Indigenous rights to be restored and commit ourselves to the journey of healing.

We thank the more than 630 First Nations, their people, and ancestors who have taken care of these lands that we share.

EXECUTIVE SUMMARY

We propose an independent institute of emerging infectious disease modellers and policy experts, with an academic core, capable of renewing itself as needed. This institute will combine science and knowledge translation to inform decision-makers at all levels of government and ensure the highest level of preparedness (and readiness) for the next public health emergency. The Public Health Modelling Institute will provide cost-effective, science-based modelling for public policymakers in an easily visualizable, integrated framework, which can respond in an agile manner to changing needs, questions, and data. To be effective, the Institute must link to modelling groups within government, who are best able to pose questions and convey results for use by public policymakers.

Quantitative models form a flexible suite of methods that can synthesize information from diverse fields, present this information intuitively and visually, support evidence-based policy, aid in communicating with the public, and quantify and manage uncertainty. Models can provide projections and scenarios and can support operational planning across multiple domains. The recent Emerging Infectious Disease Modelling (EIDM) program, created jointly by the Public Health Agency of Canada (PHAC) and Natural Sciences and Engineering Research Council of Canada (NSERC) in 2021, brought together over 100 modellers and other investigators from coast to coast. In collaboration with public health agencies (federal, provincial, and territorial), it fostered partnerships, collaboration, and trust across academic teams, government organizations, and public health institutions. It trained a high-quality workforce, and created state-of-the-art datasets and an arsenal of applied, interpretable models to support decision-making during the pandemic and beyond.

Recent experience from the pandemic underscores the need for a lasting capacity for integrated, multi-disciplinary, whole-of-society analysis that can be rapidly deployed in an emergency, with sustained and direct linkages between infectious disease research, modelling, public health, evolution, economics, socio-economics, and policymaking. We need to ensure that there is a robust, trusted platform for rapid synthesis and consensus, spanning multiple domains and scales, ready to support decision-makers and decision-making.

We envision a permanent institute to provide this capacity. In coordination with federal, provincial, and territorial public health agencies and Indigenous groups, it will:

- undertake and harmonize research in this space across institutions,
- provide funding for continued modelling and capacity-building across a broad range of expertise, and
- ensure that Canada can better deal with future crises.

The institute will be an independent, apolitical authority that can help to formulate consensus "serviceable truths" in an emergency, rapidly bringing researchers together to work on policy activities when the next crisis does occur. Its core functions will also support robust pathogen surveillance, data access, and real-time analysis, and train a high-quality workforce in the requisite scientific, communication and collaboration skills.

The Institute will connect a broad group of researchers on an ongoing basis. Importantly, its success will build upon the current bridges that have been developed between academic researchers and modellers, and those within public health agencies (federal, provincial, and territorial), who are best able to inform research directions and relay key messages to policy-makers.

The Institute will have a permanent team of administrative staff, including an executive director, knowledge translation experts, and others. Together, these groups of people will form the core of long-lasting strategic relationships between the academic community and the policy advisors. The Institute will include mechanisms for compensating researchers (or their home institutions) when they are more intensively involved, for example as director, or as advisors in times of emergency. Formation of the Institute is a crucial step towards providing cost-effective, science-based modelling that can respond to changing needs, questions and data and ensuring the highest level of preparedness for the next public health emergency.

INTRODUCTION

As the world emerges from its most severe pandemic in over one hundred years, it is important to reflect on what happened so that we can better plan for the future. The crisis of COVID-19 galvanised a broad group of epidemiological modellers from academia who interacted with the Public Health Agency of Canada and provincial health authorities across Canada to help make informed decisions. The successes that were achieved are a testament to the enormous effort and dedication shown by individuals to build the required infrastructure and relationships for effective modelling and advising. This infrastructure, consisting of research groups with the relevant scientific expertise and those skilled in knowledge transfer, needs to be maintained and strengthened so that it can be readily deployed when new crises arise.

Decisions during pandemics always require some form of modelling to integrate diverse data into an interpretable framework, to compare possible scenarios for trajectories over time, to evaluate interventions, and to estimate the likelihood of different outcomes and their associated costs and benefits. While models can be implicit, based on intuition or experience, the large number of factors at play make outcomes difficult to predict without explicitly incorporating key factors into a clear quantitative, scientific framework that can be used to make projections. Explicit quantitative models have been shown to be particularly useful when outcomes are unintuitive and policy options are not clear (e.g., informing vaccine rollout strategies (Aruffo et al. 2022a; Aruffo et al. 2022b), stay-at-home policy (Yuan et al. 2022b), school and community reopening (Yuan et al. 2022a), synergistic roles of different interventions (Tang et al., 2020), impact of public health interventions on different age groups and settings (McCarthy et al., 2020) or predicting future healthcare burdens (Tuite et al. 2020; Anderson et al. 2020; Zimmerman et al. 2021; Mishra et al. 2020)). In these cases, modellers, interacting with the broader scientific community, have a history of providing a "serviceable truth" (Jasanoff 2015), bringing together information from fields as disparate as evolutionary biology, immunology, epidemiology, and economics to formulate a scientific consensus that can help to provide a transparent and effective foundation for decision-making.

The world was caught unprepared for COVID-19 modelling, with insufficient initial capacity for connecting modelling, the broader scientific community, and public health policy. Despite this slow start, the Canadian infectious disease modelling community has had many successes during the COVID-19 pandemic. These include the establishment of the first national COVID-19 modeling rapid response task force. In concert with the PHAC External Expert Modelling Group this task force informed and enabled PPE procurement and pharmaceutical purchasing needs (Betti et al. 2021b), predicting when Alpha, Gamma and Delta variants would begin to drive rising case numbers (BC COVID-19 Modelling Group 2021; Public Health Agency of Canada 2022), quantifying the conditions on public health measures to mitigate a pandemic wave (McCarthy et al. 2020; Tang et al. 2020), aiding the design of effective vaccine rollouts (Mulberry et al. 2021; Aruffo et al. 2022b; Betti et al. 2021a), defining and communicating the benefits of "flattening the curve" (Jackson 2020), and informing cost-effectiveness of policies with long- and short-term impacts (Cotton et al. 2022; Feng et al. 2022). Canadian modellers have built many new links, for example with the COVID-19 Genomics UK Consortium (https://www.cogconsortium.uk/), the Canadian COVID-19 Genomics Network (https://genomecanada.ca/challenge-areas/cancogen/), the Coronavirus Variants Rapid Response Network (https://covarrnet.ca/), and the COVID-19 Immunity Taskforce (https://www.covid19immunitytaskforce.ca/). Importantly, they have developed collaborative links with all of the provinces (see, for example, ON Science and Modelling tables (Hillmer et al. 2021 and https://covid19-sciencetable.ca/)) and some of the territories. Models have been incorporated explicitly into provincial analyses of COVID-19 (see, for example, Government of Manitoba 2022; Government of Alberta 2021; Government of Nova Scotia 2020; Government of Prince Edward Island 2020; Government of New Brunswick 2020; Brisson et al. 2022)).

The PHAC convened weekly meetings of modellers throughout the country (the External Expert Modelling Group) to share methods, questions, results, and analyses; these meetings fostered networking in the Canadian modelling community from the start of the pandemic. These relationships provided a starting point for another success in building capacity in Canada: the Emerging Infectious Disease Modelling (EIDM) program. This joint venture between PHAC and the Natural Sciences and Engineering Research Council of Canada (NSERC) provided short-term funding to five key networks focused on public health, mathematics, statistics, One Health (human-wildlife-domestic animal-environment), evolution, and economic modelling, as well as the interactions among these themes. However, the EIDM funding is very short-term. Maintaining the strengths that have been developed requires a well-articulated long-term vision for emerging infectious disease modelling in Canada that builds on current successes and relationships.

The goal of this paper is to use our past experiences and connections to propose a long-term vision for connecting quantitative scientists and public health bodies in Canada.

WHAT IS EMERGING INFECTIOUS DISEASE MODELLING?

Emerging infectious disease modelling is the use of mathematics and computer methods to explore the transmission of disease and its health outcomes, and the effectiveness of pharmaceutical and non-pharmaceutical interventions. By its synthetic nature, modelling for public health allows the integration of economics and socioeconomics to obtain a broad societal viewpoint.

This kind of modelling uses science for action in the public health sphere. Intrinsically it provides synthetic intelligence on the transmission and trajectory of an endemic disease, outbreak or epidemic. Explicitly it assesses the impacts of different public health measures, and it explores and illustrates uncertainty in an open and transparent way.

Infectious disease modelling for public health purposes is not a simple matter of putting data, mathematics, coding and informatics together—to be effective it demands knowledge of the biological and epidemiological reality, and public health to guide it in the development of "truths" that are "serviceable" for public health policy. "Serviceable truths" are "a state of knowledge that satisfies tests of scientific acceptability and supports reasoned decision-making," while primarily aimed not at furthering scientific research but at providing a basis for action in the face of remaining uncertainty (Jasanoff 2015).

There is much to be gained from collaboration between modellers in public health and academia. Scientists undertaking disease modelling in public health and in academia have a common goal of providing the "serviceable truths" on which to base public health policies. Contributions from academia include methods, innovations, multi-model approaches, peer-review and enhanced modelling capacity. Contributions from public health modellers include an understanding of public health needs and effective communication to policy makers from public-health-based modellers. Furthermore, a community of academic modellers that is collaborative with, yet independent from public health organisations, ensures objectivity of the science underpinning the modelling. Developing a foundation for sustained collaboration in emerging infectious disease modelling between public health and academia is a key desired outcome of this paper.

BENEFITS OF CONTINUED EMERGING INFECTIOUS DISEASE MODELLING

The high value of modelling for pandemic preparedness and response has been highlighted in many jurisdictions (Centers for Disease Control and Prevention 2023; Doherty Institute 2021; Institut Pasteur 2021; Scientific Advisory Group for Emergencies 2021). Public health decision-makers recognise the importance, effectiveness, and accuracy of high-quality modelling and now routinely request modelling support to understand infectious disease transmission and to provide evidence to support policy and programmatic decisions. At the most fundamental level, the models give a way of understanding the dynamics of a disease, providing a structure for evaluating the evidence, integrating information from different fields and studies, and starting to navigate towards decisions. Models are readily presented visually; as such, modelling is ideally placed to help convey science to policymakers.

Models have key features essential to public health decision-making:

a. Models provide methods for assimilating multiple sources of information simultaneously (Figure 1). These include changing immunity within the population, the evolution of the pathogen, and the behaviour of the population in terms of mobility, adherence to government guidelines and protective measures such as vaccination and masking.
b. Models describe uncertainty in outcomes and can tell us where we need additional data to be collected to help fill in unknowns. They also provide a way of synthesizing incomplete data to good effect (Quick et al. 2021).
c. Models can be used to evaluate "what if" (counterfactual) scenarios where the outcome

of implementing alternative policies can be investigated.

d. Models can integrate disease dynamics across multiple domains (Figure 1). This includes describing immunological and epidemiological processes driving how a disease spreads and evolves, coupling disease dynamics across human-animal-environment domains via a One Health approach (One Health Modelling Network). It also includes connecting human disease and public health policy to their impact on economics, education, and the environment understand the broader set of costs and benefit associated with our responses to pandemics (Bernstein et al. 2022). Such multidisciplinary integration provided by the models can reveal t socio-economic realities in adherence to public health measures and the need to take these into consideration in the formulation of policy (Brankston et al. 2021, Murty et al. 2021)
e. Models form a bridge, translating advanced mathematical tools into a form that provides powerful tools to address problems confronting public health (Murty and Wu, 2022).
f. Models can support evidence-based recommendations as well as scientific consensus-building in many areas (a few examples include resource allocation (Asgary et al. 2021), containment, and mitigation) (Public Health Agency of Canada 2022).
g. Models can be used to communicate public health measures. Although a sustained cadre of public health modellers is crucial, public trust is strengthened when modelling and scientific consensus-building is bolstered by those at arms-length from decision-making (e.g., by university scientists). In the COVID-19 pandemic, public communication of modelling helped to bring support for public health measures, including vaccination and social distancing, by providing accurate, evidence-based information (McCarthy et al. 2020; Tang et al. 2020).

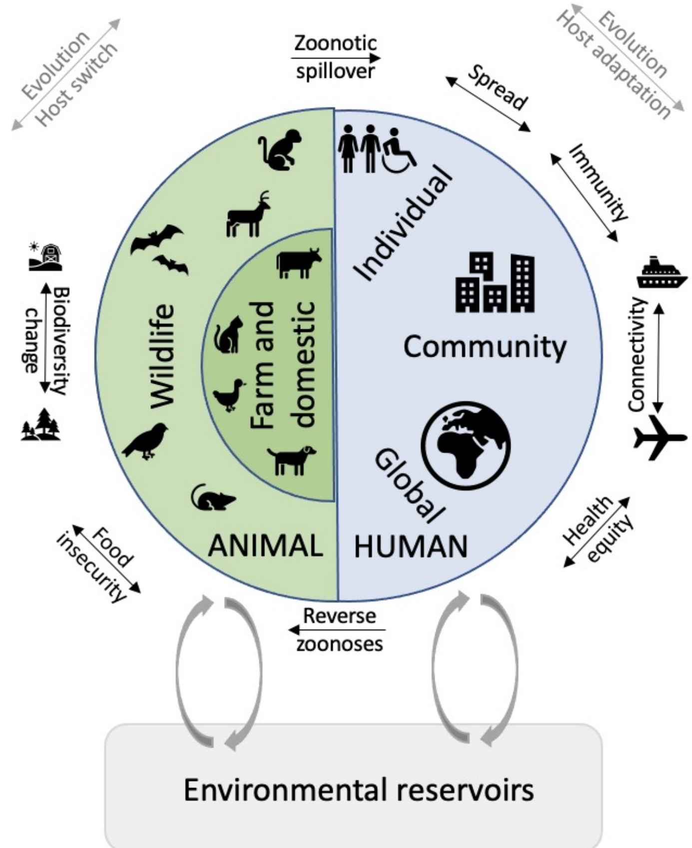

Figure 1. Emerging infectious disease models provide methods for assimilating multiple sources of information across multiple domains simultaneously.

To build lasting capacity, it is essential for researchers to be engaged in the applied research that leads them to be experts on the most salient topics, for decision-makers to identify and collaborate with experts, and to have mechanisms to facilitate rapid responses when needed. A robust and routine connection between the modelling and adjacent scientific communities is needed even in non-emergency circumstances; for example, to respond to issues ranging from vaccine hesitancy to the recent mpox and Sudan ebolavirus outbreaks to the more common outbreaks of measles, pertussis and influenza.

Recognizing the diversity of possible modelling outcomes, decision-makers require that modellers, interacting with the broader scientific community, provide "serviceable truths." Experience dictates that this is best achieved by an independent platform of advisors that is apolitical and that interfaces closely with colleagues within public health agencies, who understand both policy-makers' needs and modelling methodologies and their limitations. Such a platform can establish clear expectations about how science interacts with policy so that the details of interactions do not have to be reinvented during successive pandemics (Bhatia et al. 2023).

A successful integrated modelling community requires sustained and direct linkages among modellers, other scientific disciplines, stakeholders, and public health policy-makers—this is not just modellers doing modelling on their own. These linkages have been possible because of the direct bridge, convened by PHAC, between EIDM and modellers in government, a bridge that is anchored on the one side by the independence of academic research and on the other side by experts within public health that can ensure relevant questions are addressed, and that state-of-the-art methods are brought to policy questions. Maintaining this bridge requires a sustained core infrastructure to connect researchers as they train a strong workforce, which develops and strengthens the links, as well as continued capacity within government for successful engagement. The resulting known and trusted research infrastructure will then ensure maximum leverage of available expertise and funds when investments are made.

LEARNING FROM HISTORY

There are lessons to be learned from our historical responses to emerging infectious disease outbreaks. In 2003, linkages were developed throughout Canada between public health officials and mathematical modellers in academia in response to the SARS-CoV-1 outbreak, leading to the creation of the Centre for Disease Modelling at York University. These linkages were leveraged to grow impactful interactions between the modeling community and the then newly created PHAC and the Federal, Provincial and Territorial Committee on Pandemic Preparedness as well as those preparing rapid responses to pandemic influenza. As the concerns over major disease outbreaks declined, interactions slowly faded due to a lack of coordinated support. This was a lost opportunity for creating and sustaining a national network of experts both in academia and public health agencies that can respond quickly to emerging public health threats.

The emergence of the SARS-CoV-2 in 2019 brought this missed opportunity into stark focus. Once again, a functioning network of experts from both public health agencies and academia was built from the ground up, and the delay that resulted had real public health and economic costs. One of the greatest bottlenecks during this period was the time it took both to conduct the necessary research that decision-makers required and to build an effective pipeline through which such fundamental research and scientific expert advice could be channeled to relevant governmental decision-makers.

In addition to these lessons about pandemic preparedness, the COVID-19 pandemic also taught us that new collaborations and partnerships need to be formed, particularly between those with expertise in public health and infectious disease modelling, their adjacent scientific communities (e.g., epidemiology, immunology, public health, virology), and those with expertise in economics, education, international relations, policy-making, and the many other aspects of society that are affected by, and impact, the state of public health.

Very often during the COVID-19 pandemic, the "epidemiological good" of potential interventions was pitted against the "economic good" or the "psychological good" of not employing an intervention. In retrospect, it is now clear that in many ways this was a false dichotomy (see, for example, Sokolov et al. 2020). This mistaken perspective stemmed, in part, from the dearth of appropriate analyses that integrated infectious disease modelling with broader societal perspectives. The most powerful way to avoid similar mistakes and misinformation moving forward is to ensure that linkages between these diverse researchers are both fostered and sustained so that we can respond immediately when novel infectious disease crises arise.

SUCCESSES OF THE EXISTING EIDM PROGRAM

When the pandemic hit Canada in March of 2020, there was a desperate need from public health decision-makers for information about what might happen, and the outcomes associated with possible responses. Those working in infectious disease modelling jumped to answer these questions but found that they could not work in isolation. By seeking input from colleagues working in disparate areas – epidemiology, immunology, virology, health, economics, sociology – they were able to make more sophisticated models and to answer more complicated questions. Issues raised by different jurisdictions — territorial, regional, provincial, federal — led to development of more targeted models addressing local conditions and concerns.

Interactions between modellers led to sharing of techniques and avoidance of duplication, as well as the development of a dynamic knowledge graph (http://eidm-mmie.net/), which became a resource for finding expertise.

Recognizing the need for modelling efforts, the Emerging Infectious Disease Modelling (EIDM) program was created through a joint effort between PHAC and NSERC in 2021. There are now well over 100 primary investigators from across Canada who are part of this program through the network structure. The EIDM program has provided funding of $10M over two years to five key networks: Mathematics for Public Health (http://www.fields.utoronto.ca/activities/public-health), Canadian Network for Modelling Infectious Disease (https://canmod.net/), Statistical Methods for Managing Emerging Infectious Diseases (https://www.cghr.org/projects/statistical-methods-for-managing-emerging-infectious-diseases/), One Health Modelling Network for Emerging Infections (focusing on human-wildlife-domestic animal disease, https://omni-reunis.ca/), and the One Society Network (mathematical modelling of multi-sectoral impact of pandemics and control policies, https://onesocietynetwork.ca/). With a one-year, no-cost extension in place, the networks in this program are now entering their final year of funding.

The EIDM program has fostered linkages between academic teams, Indigenous groups, government organizations, as well as experts in several non-health sectors (e.g., agriculture, education), both within and outside the modelling community. Having these partnerships in place has reduced the length of the chain between modellers and policymakers, allowing for more rapid response to decision-maker needs. The past three years of collaboration has also established an environment of trust between the EIDM community and these partners. Such groups across Canada, including, for example the National Advisory Committee on Immunization, Health Canada, and PHAC, continue to turn to the EIDM program with their policy and research questions. The values and objectivity of the EIDM program meant these are open and transparent collaborations, where results are presented publicly and are open to criticism and commentary. These collaborations have also spurred research partnerships outside of infectious disease, including research into homeless populations and supply chain management (http://www.scanhealth.ca/).

Building Canada's knowledge capacity by training a new generation of researchers and practitioners is a key objective of the EIDM program. The large majority of the EIDM budget has gone to salaries for Highly Qualified Personnel (HQP)s. Trainees were attracted to the networks' links with the government, and the potential for having an impact on Canada's COVID-19 response. The networks recruited a very strong cohort of trainees from a range of academic backgrounds, many of whom belong to groups under-represented in the mathematical sciences. Several of these have since been employed as infectious disease modelling specialists in public health agencies and/or as university faculty. Network members integrated infectious disease modelling into their graduate and undergraduate teaching, in one case developing an upper-year undergraduate course dedicated to methods for emerging infectious disease management. Short courses on advanced topics in infectious disease modelling, such as one-health approaches, were delivered to a broad range of attendees.

The research generated by the EIDM program has resulted in an arsenal of new models (Figure 2), including compartmental epidemiological models to evaluate jurisdictions of different size and populations with different characteristics (e.g., vulnerable populations) (Wang et al. 2022; Hurford et al. 2023), in-host models to evaluate immunity, seroprevelance models to evaluate protective effects in individuals (Dick et al. 2021)), contact-mixing models to assess different feasible combinations of social distancing measures (McCarthy et al. 2020), and new models associated with emerging data (e.g., genome sequencing; pathogen sequences and concentrations in wastewater) (Nourbakhsh et al. 2022; Dean et al. 2023). Important features include sub-models for evolution (Day et al. 2020, Day et al. 2022) and competition of multiple variants, and sub-models for waning immunity from both infections and vaccinations (Childs et al. 2022; Dick et al. 2021; Korosec et al. 2022; Korosec et al. 2022; Farhang-Sardroodi et al. 2021). The EIDM networks have also been central in the development of hybrid epidemiologic-economic models that more completely assess the health impacts, costs, and trade-offs inherent in alternative policy options (Mulberry et al. 2021; Cotton et al. 2022). Some of these tools have been incorporated into provincial and federal pipelines that connect data collection to policy options. The partnerships that emerged from undertaking collaborative research with public health and health agencies and between researchers in different disciplines made the science better. While focused on COVID-19, research from the EIDM program has also provided significant new insights

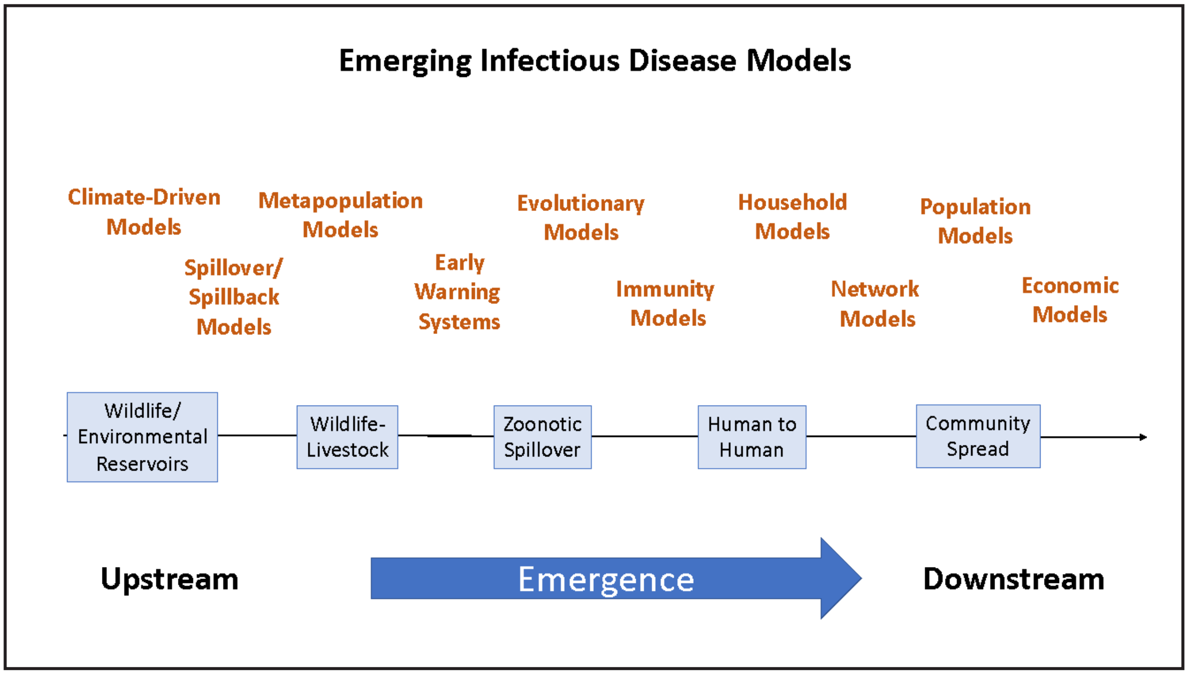

Figure 2. Emerging infectious disease models from emergence to economics.

regarding other emerging diseases such as the 2022 outbreak of mpox (formerly monkeypox) (Yuan et al. 2023; Yuan et al. 2022c).

Funding for EIDM networks has facilitated the creation of research infrastructure that, with continued support, could continue to serve the public health community in Canada going forward. The goal of the EIDM projects was to support and promote research and public health service by EID modellers––as opposed to supporting specific research agendas as typically funded by tri-council grants––and could not have been envisioned without substantial, dedicated support for EIDM. For example, one of the EIDM networks (CANMOD) has so far scanned, digitized, and cleaned all the weekly historical infectious disease notification data from Canadian provinces and territories for the period from 1924 to 2000, much of which was handwritten. These data can now be used to test modelling methodologies on historical epidemics. Other infrastructure includes a suite of R packages for visualization and analysis including an R interface for constructing and fitting complex compartmental epidemiological models without having to code many of the details (https://mac-theobio.github.io/McMasterPandemic/). This software is used by the Public Health Agency of Canada for its regular COVID-19 forecasts, as well as for modelling other emerging diseases, such as mpox, avian influenza and pandemic influenza.

Researchers from the EIDM networks have been consulted by a variety of public health and health organisations to use their modelling expertise to quickly answer urgent questions during the COVID-19 crisis. They volunteered their time in response to the emergency and engaged extensively in public outreach efforts. The funding for the EIDM network allowed researchers to support postdocs and graduate students and to dedicate the time needed to answer the urgent questions. For example, one researcher writes:

> While unfunded and volunteering my time, I co-authored a technical report (later published as (Hurford et al. 2021)) that was included in witness testimony when Newfoundland and Labrador's travel restrictions were challenged in provincial court. It was only through funding from the EIDM program that I was able to recover my research career from this voluntary time investment.
> — Dr. Amy Hurford, Memorial University.

As a group of networks, there is a potential for long-lasting impact through maintaining and growing the infrastructure of people, partnerships, innovative research, data curation and advanced modelling tools that have been developed.

VISION FOR FUTURE RESEARCH AND TRAINING IN EMERGING INFECTIOUS DISEASE MODELLING IN CANADA

To ensure a continued robust and effective capacity for infectious disease modelling, we need to create a sustainable, independent base of scientists and modellers who can be mobilized to provide science advice when needed. To provide effective advice we must ensure that the channels of communication and relationships among members as well as those in public health agencies are sufficiently well established in advance so that quick action and consensus on scientific advice will be possible in the face of unexpected and time-sensitive public health crises. To facilitate these goals, we envision a permanent institute, or a federated network of institutions, to support public health organizations in providing this capacity. This includes coordinating research in this space across institutions, providing funding for continued modelling and capacity building across departments and organizations to ensure that Canada has the capacity to better deal with future crises, and providing capacity to pull in researchers to work on policy activities when the next crisis does occur. In this section we outline the overall vision for future research and training in emerging infectious disease modelling (EIDM) in Canada, while in the next section we focus more specifically on the proposed institute.

It is important that the sustainable, independent base of modellers, described above, also collaborates with a complementary group of strong modellers and epidemiologists in public health institutions who bring the following essential elements:

- modelling with deep enough knowledge to identify the utility of modelling innovations and opportunities for application to support public health objectives;
- collaboration with academics (including co-supervising/training HQP);
- modelling methods to develop outputs and emerging consensus in public health institutions; and
- knowledge translation for non-specialist public health managers and policy-makers.

To have these elements in-house, within public health institutions, is an essential component of the "modelling ecosystem" needed to provide effective scientific advice to the government when needed.

An integral part of the creation of an emerging EIDM organizational structure will be the development of well-grounded advisory components that are sufficiently independent of government and that can convene a range of scientific experts allowing for a full airing of potentially opposing views. We envisage that most of the members of this network will likely be based at academic institutions and will participate in the network's activities as part of their own, self-directed, research programs. At the same time, when acute public health issues arise where decision-makers require prolonged and ongoing input by a member or members (e.g., the emergence of a novel infectious disease) there needs to be a mechanism through which these members can be released from their normal work responsibilities.

For the structure to be effective in providing holistic and relevant advice to decision-makers, it will need to integrate a broad range of scientific and modelling expertise. This not only includes fully integrated economic modelling (something that was lacking during the initial stages of the COVID-19 pandemic), but also integrated immunological, virological, clinical, vaccinology and evolutionary expertise. A suite of other perspectives must also be integrated from behavioural and social sciences (e.g., political scientists, sociologists, psychologists). Importantly, Indigenous perspectives and knowledge must also be included wherever and whenever possible.

Administratively, we view the future EIDM structure as an apolitical authority, recognisably independent of government, that can help to provide transparency, consensus (in the context of uncertainty and possibly multiple viewpoints), and a scientific evidence base that supports the identification of "serviceable truths" increasingly sought by public health decision-makers, particularly in an emerging pandemic context, where science is rapidly changing and decisions have society-wide impacts. Ideally this structure needs to be led by a person who is dedicated to the position full time, preferably seconded from an academic position, so that they do not lose their contact with current research. The position should rotate within the community of expertise.

EIDM requires a toolset typically not found in existing Canadian discipline-based graduate programs. Thus, a central component of our approach would be to provide our emerging workforce with holistic training that includes applied mathematics, computer science, data science, epidemiology, evolution, Indigenous health and reconciliation, infectious disease, public health, statistics and visualization. In addition, there is a need to provide experiential opportunities for trainees at all levels to conduct joint research with academic mathematical and statistical modellers, as well as across disciplines (e.g., economics, behavioural sciences), and public health/policy researchers and/or agencies. Training is needed on Indigenous knowledge, Indigenous health, and building research relationships with Indigenous communities. There is also a need to provide training for the next generation to be able to provide modelling inputs during public health emergencies. Finally, there is a vital need to include training in science communication, both for researchers and those in public health. This training would be aimed at both teaching how to convey findings in a meaningful way to the public health and policy realm, but also how to convey uncertainty about some findings.

At times of crisis (e.g., an emerging pandemic), real-time access to data relevant for modelling is essential (e.g., cases, hospitalizations, deaths, and other health outcomes; genomes of sequenced samples; economic and social variables, etc.). Mechanisms should be put in place to ensure that there is robust, ongoing, real-time surveillance, and to swiftly make all relevant new data streams available to modellers via data-sharing agreements. Ideally, we will develop automated procedures that will keep databases completely up to date going forward. Distinct from traditional disease notification data, a great deal of COVID-19 data has been made public throughout the pandemic; however, not all these data continue to be accessible on public web sites. It will be important to gather all these COVID-19 data and make them permanently accessible publicly. In addition, and recognizing that there are contexts where data cannot be immediately publicly available, models, methods and international scientific approaches can be brought in to modelling teams within public health institutions via the bridges this network will maintain.

A key way to help “do better next time” is to have in place a structure that facilitates building trust and an awareness of the expertise of others. For example, we need to make it easy for journalists to find the right people to interview, for modellers to identify appropriate collaborators in public health (and vice versa), and for trainees at all levels to find suitable programs, academic advisors, or job opportunities in public health. We have an online structure already in place to help build the connections (our network graph at http://eidm-mmie.net/) but continuing to support its development and expansion will make it a more powerful resource. A well-maintained network graph will make it possible for anyone to identify the cadre of Canadian scientists who have modelling expertise, understand the policy process, and have connections to international networks.

Modellers within public health and in academia must have, individually or collectively, the best mathematical methods, the data, and, in one form or another, the epidemiological/ecological/biological context of the system they are exploring. This is more than bringing mathematics and data together — for this to be successful, it will require a sustained funding model.

CALL FOR INVESTMENT IN A PUBLIC HEALTH MODELLING INSTITUTE

We need to be a nimble and responsive scientific community that is funded to do interdisciplinary and policy-facing core research in emerging infectious disease modelling. To achieve this, we propose to create an institute to build on the successes and structures of the existing EIDM networks, in combination with a convening and coordinating central structure that will reduce administrative overlap and will enable some new key functions.

Some examples of the mandate of this central institute structure include building and maintaining strategic partnerships, coordination of the EIDM community and knowledge translation, data management and organization, and supporting rapid policy response through consensus building. This structure will also allow the EIDM community to fund exciting and competitive new programs, including embedded fellowships for senior and junior researchers to learn about new research fields, salary support for faculty to address policy needs, research chairs or tenure track hires, partnerships with government, policy, public health, and industry, as well as the development and delivery of training in a range of contexts.

Specifically, we propose to create a Public Health Modelling Institute. The Institute would have dedicated staff supporting six core functions:

1. The Institute would be a central coordinating resource, convening the EIDM community, organizing network-wide events, and promoting the ongoing work of the community by providing a searchable and interactive visualization of the individuals involved and their activities. Moreover,

it would provide an opportunity for members of the community to be released from their regular positions to spend time exclusively involved in advancing the discipline.

2. The Institute would cultivate and maintain strategic relationships with partner organizations and agencies. This would include the key national agencies (Public Health Agency of Canada, Health Canada, Statistics Canada, National Microbiology Laboratory, National Research Council) and research-supporting bodies such as the four mathematics institutes, the Canadian Statistical Sciences Institute, the Canadian Institute for Health Information, and the Digital Research Alliance of Canada. Additionally, provincial public health institutions and health authorities, other national-scale pandemic-related groups (Canadian Immunization Research Network (CIRN), Centre for Research on Pandemic Preparedness and Health Emergencies, Coronavirus Variants Rapid Response Network (CoVaRR-Net), National Collaborating Centre for Infectious Diseases (NCCID), Covid-19 Immunity Task Force (CITF)), pandemic-focused institutes (Pacific Institute on Pathogens, Pandemics and Society (PIPPS), University of Toronto Institute for Pandemics, McMaster Global Nexus for Pandemics and Biological Threats (https://globalnexus.mcmaster.ca/), York Emergency Mitigation, Engagement, response, and Governance Institute (Y-EMERGE), Canadian Centre for Disease Modelling (CDM)) and local public health agencies would be engaged.
3. Knowledge translation (KT) from the Institute's research would be supported by KT experts and coordinated centrally.
4. The Institute would participate in the ongoing conversations about the future of health and infectious disease data in Canada. It would bring the perspective of our scientific community to these conversations, conveying what data are available to our researchers and arising from our research and articulating the additional gains that would come from increased data availability.
5. The Institute would facilitate rapid policy response and requests for advice by convening the relevant parts of the community and providing a framework for building a broad consensus and identifying "serviceable truths". It would have a mechanism to ensure that resources can be made available, that the expertise required can be easily identified and accessed at short notice. Furthermore, the institute would coordinate public communication, which enhances the impact of research, builds trust with the public, helps to combat misinformation, and inspires interest in applied and interdisciplinary science.
6. As an Institute, the necessary partnerships with Indigenous communities and other equity-focused groups would be cultivated by coordinating with partners working in this space including CoVaRR-Net's Indigenous Engagement, Development, and Research Pillar 7 (CIEDAR) and Global One-health Network (G1HN).

The Institute would emphasize and prioritize interdisciplinary projects and programs. It would interface among biostatistics, data science, drug therapy, economics, epidemiology, evolution, genomics, health, immunology and virology, mathematics, and vaccine development. In integrating diverse sources of knowledge, and through building the partnerships we envision, the Institute would leverage large existing investments in genomic sequencing, serological studies, biomanufacturing and wastewater surveillance, among others. It would build on the strengths of the EIDM networks that have already been established and would particularly support work that builds the research-policy bridge. Similarly, the Institute's research activities would link to growing industry-facing activities in biotechnology, biomanufacturing, and the financial industry.

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APPENDIX A: FUTURE RESEARCH AND CHALLENGES

Going forward, we envisage EIDM activity outside the context of a public health crisis. We believe such activity should embrace the entire spectrum of disease topics – within wildlife, between wildlife and livestock, between livestock and humans, within and among humans (Figure 1), and evolution pre- and post-human to human transmission. At the human level, the activity should be shaped by social context and interventions (such as vaccinations, past infection, selection favouring immune escape and behaviour). Human society in turn shapes the infectious disease risks from wildlife, through our impact on the climate, ecology, increasing human density, and encroachment into areas where wildlife live (Figure 2). EIDM researchers in Canada have expertise in many of these aspects. This expertise must be mobilized in terms of research, training, and relationships.

The existing EIDM networks have successfully demonstrated that a policy committee chaired by public health academic leaders and populated by provincial and federal public health officials is able to interact effectively with researchers in a bidirectional manner. This kind of structure will remain essential to facilitate effective interaction between researchers and public health.

The research activity of the future EIDM may be envisaged in a quadrant (Table 1):

- there are *established* objectives from public health (e.g., model projections of disease trajectories under a range of scenarios) that can be answered by researchers using *established* methods (e.g., compartmental infectious disease modelling with simple assumptions about the population structure and mixing)
- there are *emerging* objectives (e.g., determine the connection between public health measures and economic activity) that can also be answered through *established* methods, perhaps applied in a novel manner (e.g., dynamic input-output models from economics)
- there are more challenging *established* objectives (e.g., evaluate early indicators of disease spread) that require *emerging* methods (e.g., new advances in artificial intelligence/deep learning)
- finally, there are *emerging* objectives (e.g., assess methods for increasing vaccine acceptance in heterogeneous populations with differing decision-making dynamics) that will require significant research effort to address, likely using *emerging* methods (e.g., new ways of coupling evolutionary game theory to epidemiological models).

It is essential that EIDM activity should continue to embrace communication and knowledge translation. During the pandemic, researchers have recognized the need for communication across different scientific fields, institutions, and geographies. Within Canada, lessons have been learned in understanding the different dynamics in different parts of the country such as in Atlantic Canada and in Indigenous populations.

EIDM activity must also align itself and engage with the Calls to Action outlined in the 2015 *Truth and Reconciliation Report* (Truth and Reconciliation Commission of Canada 2015). Key elements will involve building partnerships with Indigenous communities, educating researchers about the principles of reconciliation, and training researchers on Indigenous knowledge, Indigenous health, and building research relationships with Indigenous communities.

A common experience of researchers during the pandemic was the difficulty of accessing data. The situation is complicated with privacy and ethics considerations affecting collection and sharing of data, including lengthy institutional delays on approvals. The resolution of these issues goes beyond science, and perhaps into the legislative or political arena. Ideally, if an umbrella agreement between relevant parties could be negotiated and implemented this would significantly alleviate the difficulty of data access. Moreover, computational resources necessary to support data analysis, simulation, and the generation of synthetic data, need to be negotiated.

To ensure Canada's alignment with its international partners, it is necessary to have institutional level agreements for sharing of best practices and modelling efforts. These communication efforts will support the work of PHAC, as well as its provincial and regional counterparts, and affect knowledge translation within government.

	Established objectives	Emerging objectives
Established methods	1a. Objective: project disease outcomes under different levels of transmission and contact; 1a. Methods: deterministic compartmental disease modelling (Zhang et al. 2022) 1b. Objective: forecast disease and mortality levels; 1b. Methods: machine learning, dynamical systems (Ramazi et al. 2021) 1c. Objective: evaluate effectiveness of contact tracing in different epidemiological contexts; 1c. Methods: branching process models; compartmental SIR model (Bednarski et al. 2022) 1d. Objective: determine interaction between human behaviours and healthcare burden; 1d. Methods: agent-based models (Silva et al. 2020)	2a. Objective: assess impact of public health measures on economic activity; 2a. Methods: dynamic input-output models from economics (Santos 2020) 2b. Objective: make joint epidemiological-economic scenario projections for a new pathogen; 2b. Method: agent-based models (Bedson et al. 2021) 2c. Objective: evaluate early indicators of disease spread; 2c. Methods: artificial intelligence/deep learning, statistical methods (Bury et al. 2021) 2d. Objective: assess within- and between-host dynamics of EID based on immunology and evolution; 2d. Methods: Multiscale models incorporating deterministic, stochastic and trait-based components (Handel and Rohani 2015) 2e. Objective: evaluate how rapidly a new variant will rise and its public health consequences; 2e. Methods: integrated evolutionary and epidemiological models (Day et al. 2020; Day et al. 2022; Otto et al. 2021)
Emerging methods	3a. Objective: evaluate zoonoses disease risk from a One Health perspective; 3a. Method: integrative (3P—process-pattern-participation) models (Scoones et al. 2017) 3b. Objective: determine optimal control methods using engineering feedback principles; 3b. Methods: feedback theory (van Heusden et al. 2023) 3c. Objective: assess which virus phenotypes are most strongly favoured by evolution in different epidemiological circumstances; 3c. Methods: phylodynamics (Attwood et al. 2022) 3d. Objective: evaluate interacting social and infectious disease challenges (syndemics); 3d. Methods: composite "meta-methods" (Lepelletier et al. 2022) 3e. Objective: estimate detection rate and population size; 3e.Methods: N-mixture (hidden Markov) type models (Parker et al. 2021)	4a. Objective: assess dynamics of vaccine acceptance in heterogeneous populations; 4a. Methods: couple evolutionary game theory to epidemiological models (Aghaeeyan et al. 2023) 4b. Objective: evaluate impact of NPI policy on future disease outcomes; 4b. Methods: dynamical systems coupled to machine learning (Wang et al. 2022) 4c. Objective: evaluate impact of social distancing on the optimal vaccine rollout strategy; 4c. Methods: agent-based models coupled to equation-free methods (Spiliotis et al. 2022) 4d. Objective: assess how systemic inequalities amplified by the pandemic be best addressed; 4d. Methods: urban systems abstraction hierarchy (Beevers et al. 2022)

Table 1. Established and emerging objectives and methods in public health modelling, with examples of contributions from the EIDM network. The table shows some representative objectives and methods but is by no means complete.

APPENDIX B: ENSURING THAT EMERGING INFECTIOUS DISEASE MODELLING IS TRANSLATED INTO PUBLIC HEALTH GAINS

There are two distinct mechanisms for modelling and, more broadly, for science to directly inform policy in a pandemic or similar emergency: (i) close and direct collaboration, likely led by government or public health institutions and likely focused on building tools to answer specific research-to-policy questions, and (ii) consensus building at a wider scale with a broader community of academics including modellers and others.

In the close collaboration model for knowledge translation, public health epidemiologists, scientists, and modellers work side-by-side with academic partners either in virtual or physical spaces (or a combination of the two) to ensure seamless flow of public health needs, data, innovations, and modelling solutions. This creates outputs of great direct use for both public health and academia and also provides impetus for innovations in modelling.

In the consensus building model for knowledge translation, modellers develop multiple models and viewpoints in response to emerging threats, current focal questions and requests from decision-makers. This is a key part of the scientific and analytic process. For their part, researchers need to recognize that policymakers need a platform for timely decision-making based on a synthesis of models that enjoys consensus support within the academic community. Such a synthesis is not the endpoint of inquiry: rather it is a consensus view at a point in time that is both scientifically valid and "serviceable" for the purposes of informing policymaking (Jasanoff 2015). This means that the process for achieving this consensus needs to be inclusive of a range of modelling centres and networks. In contrast to close and direct collaboration, this approach needs to be sufficiently independent of government that it has credibility within the scientific community and with the public. However, scientists should expect that ongoing conversations with policymakers will inform and enrich the boundary between science and policy. Policymakers, on their part, need to recognize that there will be considerable uncertainty, particularly on short time frames, and differences of opinion and dissent will occur as the science continues to develop. However, they should be able to expect a synthesis of advice that flows from models, relevant to a particular question. The network we envision will support these activities.

More broadly, models play a role in building and communicating scientific consensus and "serviceable truths", because of modelling's ability to synthesize diverse data, explore the consequences of assumptions, quantitatively test assumptions against data, and incorporate information as it emerges. In this context, the modelling and scientific communities can support decision-makers by coming together to create platforms for decision-making, rapidly assessing these through formal or informal peer review and robust debate, and by coming to agreed conclusions that are informed by this evidence and transparent process.

Workshops and training are essential ingredients for knowledge translation in EIDM. They operate in both directions: training public health epidemiologists to build knowledge of modelling and training modellers to build knowledge of epidemiology and public health. This needs to be ongoing and provide core training for HQP. Activities include development of simulated pandemic exercises to underpin greater pandemic preparedness and mutual understanding of modelling for public health in day-to-day and emergency outbreak situations. They also need to include development of skills in communication to the public for both academics and public health professionals.

There are some essential organizational ingredients that are predicated by the above framework for knowledge translation to ensure long-term success in translating EIDM into public health gains.

- Public health and researchers must collaborate to develop a secretariat function that facilitates "evergreen collaboration" with academia (e.g., regular communication activities) and to ensure decision-makers obtain clear and consensus messages from the modelling community.
- Productive interactions with the EIDM community require that there are people embedded in public health and government who understand and appreciate the strengths and limitations of modelling.
- Federal public health institutions need to provide the opportunity for links with the global community in public health and international benchmarking of methods.