Government of Canada / Gouvernement du Canada

**APPLICATION**
**Proposed Research Program** (15 pages)

| Institution: | University of Alberta |
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| Title of proposed CERC: | Open Science and Meta-science in Ecology and Evolution |
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## 1) RESEARCH PLAN

### a) Executive summary:

This CERC program aims to revolutionize the way research is conducted in ecology & evolution, and addresses the challenge of replication via open and team science. This program will quantify the robustness and replicability of ecological & evolutionary evidence by building up innovative statistical and AI-assisted tools, and inclusive team-science communities. These activities will lead to a global network of researchers to make ecology and evolution more robust and trustworthy. Thus, the program will provide significant benefits by establishing a collaborative knowledge hub for ecology & evolution in Canada, directing the future of ecology, evolution, and related fields (e.g., climate change).

### b) Context:

**Over the last several years, high-profile studies have repeatedly reported low replicability of scientific results.** For example, a study in *Nature* reported ~90% of landmark cancer biology studies (47 out of 53) were not replicable[1], and a *Science* paper reported that 68 of 100 psychological experiments did not replicate[2]. A *Nature's* survey of 1,576 researchers across fields revealed that, on average, ~70% of them had experience not being able to replicate another researcher's experiments while >50% could not replicate their own[3]. These figures shocked scientists but were also presented as a 'crisis' by the media. Such negative media coverage has undermined public trust in science, which is more important than ever, especially amid the current pandemic.

**However, these findings of low replicability have generated momentum** to organise a series of large-scale replication efforts across different topics and fields[4-7]. Furthermore, these efforts have accelerated the movements towards more scientific transparency and openness (i.e., open science). Indeed, open science has recently created a radical shift in how scientists conduct and share research with more scientists working collaboratively on a global scale (i.e., team science) [8]. These positive changes are referred to as a '**credibility revolution'** or **'innovation opportunity**'[9,10]. Notably, the credibility revolution corresponds with the rise of meta-science, also known as meta-research (research on research)[11]. Meta-research's mission is to improve scientific processes and, therefore, to improve science by finding and acting upon research ineffectiveness, errors, biases, and gaps[12].

**Dr. Nakagawa has been leading meta-research in ecology and evolution**[13-16]**.** Unlike medical and social sciences, it is challenging, if not impossible, to conduct a replication effort at a large scale in ecology and evolution[17] partially because the field deals with all the diversity of life rather than the one species, human beings[14,18]. Yet, meta-research work, conducted by Dr. Nakagawa and colleagues, suggests that low replicability is likely for ecology and evolution. On average, ecological and evolutionary studies have inflated significant effects by three-fold, and very low statistical power of ~20% (among the lowest estimated across different fields)[19]. Furthermore, the survey revealed that >60% of ecologists and evolutionary biologists engaged in questionable research practices (e.g., selective reporting, hypothesising after the results are known, and *p*-hacking) [20]. **These findings call for a concerted effort for a credibility revolution in ecology and evolution.**

**Meta-scientific studies across the fields have identified several key reasons for low replicability**[21]. These are: 1) due to the focus on statistical significance, ~50% of research is never published[22], 2) *p*-hacking and cherry-picking leads to artifactual results, 3) poor and selective reporting creates gaps in information[23], and 4) inadequate study design and analysis are rife probably due to insufficient quantitative training[19,24,25]. In addition, poor archiving practices (e.g., the lack of meta-data) make it difficult to reuse data[26]. Archived properly, research data can be repurposed, for example, for individual participant data meta-analysis and other types of data syntheses and integration, leading to new discoveries. Yet, such 'data recycling' on raw data is uncommon, although the number of meta-analyses is steadily increasing. Importantly, current meta-analyses focus almost exclusively on average changes in an intervention or of a phenomenon. Other aspects of data such as (co)variance and skewness are rarely synthesised, with most datasets failing to attain their full potential.

**Therefore, an overarching theme of this program is to orchestrate and propel a credibility revolution in ecology, evolution, and related areas (e.g., conservation) via four broad goals:** *A) creating a reliable knowledge map, B) improving research replicability and efficacy, C) normalizing open and community-based science and D) facilitating data recycling via new statistical methods.* Dr. Nakagawa proposes to conduct the first systematic and large-scale meta-science project in ecology and evolution by building diverse and global networks to achieve the following four specific aims:

**Aim 1.** *Map the current state of knowledge and evidence in ecology and evolution and establish an open community to conduct the first 'living' evidence synthesis by creating an international network of scientists and non-scientists (e.g., targeting high school students to increase STEM uptake).*

**Aim 2.** *Predict replicability or confidence in published evidence in empirical studies and meta-analyses in ecology and evolution, and then validate the replicability of some of the meta-analyses via a series of workshops that both conduct and teach meta-analyses.*

**Aim 3.** *Build scientific infrastructure to increase replicability by creating a semi-automated AI-based synthesis workflow, reporting guidelines & best practices, and the first pre-registration repository for ecology, evolution, and related fields.*

**Aim 4.** *Develop a new set of statistical methods for meta-analysis that enable 'data recycling' in a wide range of fields, including environmental, social, and medical sciences, and showcase how these new methods can also expand and bring SGBA+ (Sex or Gender-Based Analysis plus) to the next level.*

**Although this CERC's focal field is ecology and evolution, the program is trans-disciplinary**, and the proposed scientific infrastructure will have an enduring legacy. Computer and data scientists will play a crucial role in AI-assisted semi-automating evidence synthesis and building computational infrastructure to improve replicability. Notably, for the initial period of the CERC (8 years), Dr Nakagawa will focus on a sub-field**, evolutionary ecology** (especially for Aim 1-2), which exists at the intersection between ecology and evolution, paying particular attention to organismal interactions and evolutionary histories. Yet, he plans to extend the spirit of open and team science by building reliable knowledge maps and quantifying replicability in other fields of *ecology, evolution, conservation, and environmental sciences* beyond the lifetime of the CERC.

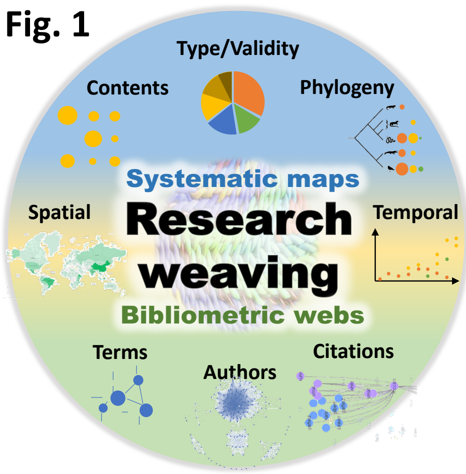
**c) Significance and Innovation:**

This section introduces the three aspects of each of four aims (Aim 1-4) described above: I) *Significance*, II) *Innovation & Activities* and III) *Methodology*. Each aim consists of three activities (sub-aims; therefore, in total, 12 sub-aims). Aim 1 & 2 focus on creating a reliable knowledge map in **evolutionary ecology** while Aim 3 & 4 build a range of scientific infrastructure by developing statistical & computational methods, best-practice guidelines, and their easy-to-use implementations, which are relevant to all the sub-fields of **ecology and evolution, and beyond**. All activities are aimed at increasing research efficacy and facilitating data recycling, therefore, sustainable research practices, via the principles of open and team science.

**AIM 1: Mapping a new overview of evolutionary ecology via team science**

***Significance for Aim 1:*** A rapid increase in both primary (research) and secondary (review) literature in evolutionary ecology presents an opportunity and challenge when summing up evidence. Although excellent reviews and textbooks for the field exist, we currently lack a systematic catalogue of evidence in ecology and evolution. Further, no reviews and textbooks are continually updated, becoming quickly obsolete. If publication bias is prevalent, any synthesis of these will provide a distorted view of the field.

Fig. 1




How researchers effectively and systematically summarise evidence? If they could do so, how could such a summary be kept up to date? Finally, what if available evidence is biased due to selective publication? These issues are not confined to ecology and evolution, and this proposed work will be an exemplar for any field of study.

***Innovation & Activities for Aim 1:*** To address the problems above, the CERC team will use the two original and widely applicable concepts, both of which Dr Nakagawa has recently proposed: A) **research weaving**[27] (**Fig. 1**; for more details, see below) and B) **an open synthesis community**[28].

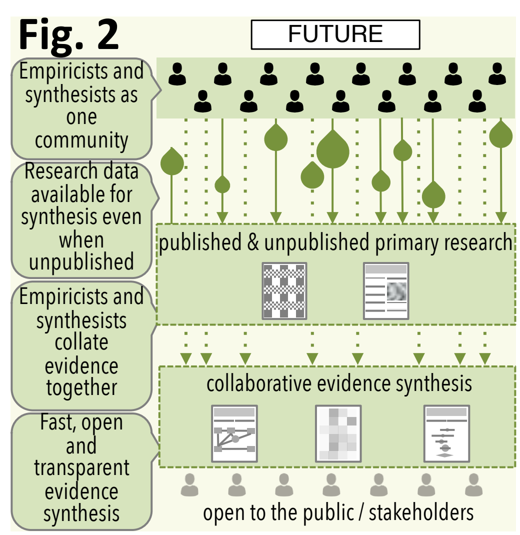
**Research weaving** allows us to summarise information content, history, and networks among a collection of documents on any given topic. This is achieved by combining the strengths of two methods: *systematic mapping* and *bibliometrics*. Systematic mapping provides the current state of knowledge and evidence, identifying areas with more research gaps and clusters. On the other hand, bibliometrics enables us to see how pieces of evidence are connected. Such bibliometric webs reveal the structure and development of a field and what scientists are involved in a particular field and how influential their work has been.

An advantage of research weaving over simply conducting a systematic review/map is that one can gain more in-depth insight into the literature in terms of both research content and the key researchers (**Fig. 1**; the upper/blue area belongs to a systematic map; the lower/green area belongs to bibliometric analyses; the yellow area is where they come together in research weaving and are shared by both systematic maps and bibliometric webs). Research weaving will make research results accessible to stakeholders and the public due to its focus on visual summaries and its dynamic and interactive nature. Using research weaving, the CERC proposes to conduct what is often referred to as an overview of reviews, or a second order synthesis[27] by:

**Aim 1.1:** *Systematically and bibliometrically mapping all the (narrative) reviews, collating a database of all meta-analyses (quantitative reviews) in evolutionary ecology and evaluating their quality (or risk of bias).*

This map and database will elucidate knowledge clusters, gaps, and biases, where we can focus attention, and guide the future studies in evolutionary ecology. Within this CERC program, this activity (Aim 1.1) will help in identifying key primary studies and all meta-analyses, respectively; meta-analyses are starting to replace traditional (narrative) reviews due to its ability to test and build hypotheses. Both primary and meta-analyses will be used in Aim 2.

**An open synthesis community** comprises both researchers conducting research (empiricists) and researchers synthesizing research (synthesists), and in such a community, empiricists see their work as a part of a much larger puzzle to be solved (**Fig 2**). Therefore, empiricists will design, conduct, and report their work accordingly. Dr Nakagawa has proposed the three advantages of such communities: 1) both *disappointing* and *exciting* results will be a part of the syntheses, improving research efficacy and overcoming publication bias that skews our knowledge, 2) as the community is open to all including historically marginalised peoples, it will increase diversity in participation and reduce inequality in research opportunities, 3)

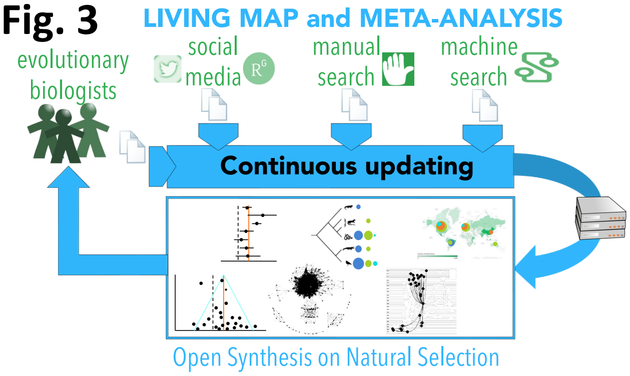


it will enable syntheses to stay up-to-date, because empiricists upload their own results and they will be rewarded with co-authorship or more accurately, contributorship[29]. Given these, the CERC team will:

**Aim 1.2:** *Create the first open synthesis community* to enable a *continuously updated meta-analysis in ecology and evolution (currently, no open synthesis community exists in any field).*

This first ever open synthesis community will aim to synthesize all selection coefficients obtained from field research across the globe, measuring the strength of natural selection in real-time. Significantly, this activity can detect changes in selection pressure on an ecological timescale. Such global monitoring is extremely important under our rapidly changing climate and environment.

Fig. 3




Aim 1.2 will be a 'living' (continuously updated) review[30,31]. The team will set up a web platform for this living meta-analysis (see **Fig 3**; for scalable and generalizable computational implementation, see Aim 3). On this platform, they will recruit ecologists and evolutionary biologists to be a part of the open community (e.g., using Zooniverse [32]). Then, these recruited members will be encouraged to engage in citizen science activities, especially targeting high school students via school visits across the world (e.g., discussing the importance of the project & inviting field trips to their research sites), increasing students' STEM participation and aspirations. In this way, our outreach via this activity will be both local and global (a special team for this activity will be formed; see Section 4).

In addition to these high school visits, Dr Nakagawa will lead a team of researchers that:

**Aim 1.3:** *Map Canadian high school and actual practice in teaching evolutionary theory, high school students' understanding of the theory, and co-create educational materials based on local 'evolutionary ecology' examples with local teachers & researchers and Indigenous peoples.*

This aim will be the first comprehensive survey of this kind, focusing on teaching and understanding of evolutionary theory across Canadian high schools (see Section 7 on how the CERC team will work with Indigenous peoples).

***Methodology for Aim 1:*** For synthesis activities (Aim 1.1), the team will use a systematic-review approach to obtain relevant publications. This approach has been detailed in Dr Nakagawa's group's recent publication[33]. Using both *Scopus* and *Web of Science* databases (searched in Jun 2022), Dr Nakagawa estimated the number of papers to be screened as *ca.* 50,000 for (narrative reviews) and *ca.* 5,000 (meta-analyses), containing an estimated 5,000 papers and 500 papers for further extraction, respectively. In addition to multiple-database searches, including the grey literature databases, the team will also conduct forward and backward searches of relevant papers[34]; These systematic search strategies will provide a fairly comprehensive view of the most current literature in evolutionary ecology. The team will also assess the quality of meta-analyses in evolutionary ecology, which will be done by using a modified version of *AMSTAR2* (Assessing the Methodological Quality of Systematic Reviews version 2)[35] *and CEESAT* (Collaboration for Environmental Evidence Synthesis Assessment Tool)[36], in a similar way to Dr Nakagawa's earlier work[37].

For Aim 1.2, the CERC team will use the published database as a starting point; this database compiled by Dr Adam Siepielski (a key and current collaborator) has >10,000 estimates of selection coefficients from 160 populations across the world. As mentioned above, Aim 1.2 will use a *living* synthesis platform (Fig 3), which will be computationally implemented in Aim 3.1 (see below). Also, the team will incentivise participation through the process akin to a coauthorship-incentivised mega-project, CIMP (described in Aim 2), by working with learned societies such as *the Society of Open, Reliable, Transparent Ecology and Evolutionary biology* (SORTEE), *the Study of Evolution, the European Society* *for Evolutionary Biology, the International Society of Behavioural Ecology,* and *Canadian Society for Ecology and Evolution.* For Aim 1.3, the team will work with Dr Mark Higgins (core team) and use questionnaires to quantify the gap between the curriculum and the practice of high school education of evolutionary theory, students' understanding of the theory and its implications.

**AIM 2: Discovery how trustworthy and replicable the current scientific evidence is**

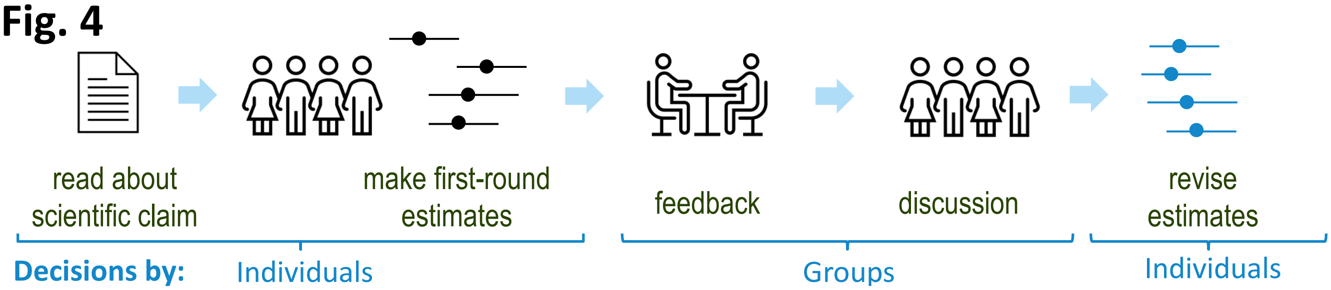
***Significance for Aim 2:*** Although replication has been labelled as the cornerstone of science[38], very little research has been done on replication itself. Two broad classes of replications are: close (exact) replication and conceptual replication[39]. The former attempts to repeat the original study in the same manner, while the latter change and/or extend some aspects of the original study. Close replication studies have been rare in science[40,41]. However, this is rapidly changing in social and medical sciences, as exemplified by recent large replication efforts[2,5,6].

The field of ecology and evolution is seriously lagging in this aspect. A recent survey suggests that an estimated close replication rate is 0.023% in ecology and evolution[42], although 97% of ecologists and evolutionary biologists consider that replication is important[43]. This extraordinarily low rate of replication may not be surprising, as close replication is impractical, or sometimes impossible, in ecology and evolutionary biology; this issue is termed as the 'one earth' problem because many ecological and especially evolutionary events are contingent upon particular space and time[17]. But is there an alternative to replication? If there exists a good alternative, how can we validate its accuracy? Is the alternative logistically implementable?

***Innovation & Activities for Aim 2:*** To address these questions, the CERC team will use three innovations: 1) a structured survey method platform, termed *Replicating EcoEvo,* 2) a new way of project participation, *a coauthorship-incentivised mega-project* (CIMP**;** or more accurately, contributorship rather than coauthorship[29]), and 3) combining educational and research workshops: *Dual Education And Research,* DEAR *workshop.*

**Replicating EcoEvo** will be a platform for predicting the replicability of empirical and meta-analytic studies in ecology and evolution (initially, focusing on evolutionary ecology). It will implement a structured and iterative elicitation and aggregation of expert opinion, or the IDEA protocol[44,45]. IDEA stands for 'Investigate', 'Discuss', 'Evaluate', and 'Aggregate', representing the four steps of the survey (**Fig 4**); the IDEA protocol has been used successfully in political and environmental risk assessments[46] (notably this protocol is robust against groupthink and other biases). A preliminary result shows the IDEA protocol can predict direct replicability with an 84% hit rate in social science studies.

**Fig. 4**




Currently, the IDEA protocol has only been applied to predicting (close) replication. Yet, replication in ecology and evolution adds a complication, as Dr Nakagawa described in *BMC Biology*: quasi-replication is commonplace in ecology and evolution where researchers use different species to test the same hypothesis[14]. While close replication can test the *validity*, conceptual or quasi-replication can test the *generalizability* of a finding. By using the IDEA protocol, the CERC team will:

**Aim 2.1:** *Quantify replicability of ~2,000 key empirical studies in evolutionary ecology in terms of different levels/types of replications (close, conceptual and quasi-replication);*

**Aim 2.2:** *Quantify replicability of ~500 meta-analyses in evolutionary ecology in terms of close replication.*

Combined with Aim 1.1, **Aim 2.1-2.2 will create a reliable knowledge map of evolutionary ecology,** which will elucidate where scientific evidence is weakest and strongest; future studies can direct their efforts accordingly, and it will stop evolutionary ecologists from building their science on weak foundations.

**A coauthorship-incentivised mega-project (CIMP)** is a new way of collaboration via a registered report that is an emerging publishing model where the project idea and method are reviewed and later accepted for publication, regardless of whether the results are *exciting* or not[47,48]. This new way of encouraging participation in a project has already proven to be extremely effective. Dr Nakagawa has already been working on such a CIMP. Dr Nakagawa & his colleagues have a Stage-1-accepted registered report in *BMC Biology*, where they ask volunteer scientists to analyse one dataset in ecology and another data set in evolutionary biology, with a promise of co-authorship. They analyse one of the two datasets and then participate in assessing other analyses (cf. [49]). More than 220 people dedicate an estimated 20 person-hours (~4,000 hours in total). Therefore, CIMPs will enable Aims 2.1-2.2.

**Dual Education And Research (DEAR) Workshop** is a unique initiative where the CERC team will not only teach, but also collaboratively replicate meta-analyses with ECRs from around the world. EDI will be a central consideration for these workshops; workshops will be advertised broadly, including through networks that aim to increase representation from systematically excluded groups (e.g., Canadian Black Scientists Network) and workshop will strive to have good global representation, including researchers from the global south. Subsidies will be offered to promote participation by scholars from Developing Nations (based on World Bank Income Categories), and some worships will be held virtually to further enable global participation, and provide accessible options for people with caregiving responsibilities, disabilities, health concerns, or other barriers that make in-person participation challenging.

These workshops will be held biannually over 7 years (14 workshops in total), where relevant experts and ECRs are invited to learn and conduct a meta-analysis. Thus, this workshop will train ECRs in cutting-edge synthesis methodologies, conduct and coordinate research synthesis projects and support their careers through publications. For each workshop, they will invite ~21 people who will be separated into three groups of 7 people, consisting of one expert in a particular topic and 6 ECRs (these ECRs can come from this CERC's partner organisations). The CERC team with workshop participants will:

**Aim 2.3:** *Update (replicate) 42 meta-analyses to validate replicability quantified in* Aim 2.2.

This activity will result in updated & high-quality meta-analyses of 42 important topics in evolutionary ecology. At the same time, it will train > 250 ECRs globally in research synthesis via 14 DEAR workshops. Importantly, ~ 1/3 of these 42 meta-analyses will be reserved for the issues of climate change and/or conservation ecology, directly relevant to two focus areas of the CERC's *Science, Technology, and Innovation Priorities*. Via this aim, the CERC team will collaborate with partner organisations such as Alberta Environment and Park, Alberta Conservation Association, and Environment Canada and Climate Change, addressing their interest and needs at the same time.

***Methodology for Aim 2:*** For Aim 2.1, the CERC team will collect key evolutionary ecology empirical studies using textbooks in evolutionary biology and evolutionary/behavioural ecology (e.g., [50-54]), as well as targeting highly cited papers on particular topics (identified by the bibliometric analysis in Aim 1.1). For Aim 2.1, the CERC team will use ~500 meta-analyses in evolutionary ecology, identified in Aim 1.1. Each assessment takes 0.5 hours, which means 4,000 person-hours (2,000 studies x 4 people x 0.5 hour) are required for this objective. Therefore, Dr Nakagawa plans to write a Stage-1 registered report for both Aim 2.1-2.2. Then, he will recruit collaborators who will assess replicability of the collected studies via CIMPs. Importantly, the team will create an online platform for these activities, *Replicating*

*EcoEvo* will build upon repliCATS[55] (Collaborative Assessment for Trustworthy Science) that has implemented the IDEA protocol.

For Aim 2.3, our team will update (or replicate) 42 meta-analyses with various degrees of replicability, quantified in Aim 2.2; the team plan to include non-English publications as a part of these replication efforts in the light of Dr Tatsuya Amano's work[56,57] (a current collaborator of Dr Nakagawa). One update would take ~500 person-hours, which means ~21,000 person-hours to replicate 42 meta-analyses (Aim 2.3). A series of DEAR Workshops will enable the completion of such a monumental task. During each workshop, the CERC team aim to semi-complete a meta-analysis replication over 5 days (e.g., extracting all effect sizes) by all participants working together (Dr Nakagawa's lab can prepare some of the early stages of replication prior to workshops). Note that studies have shown Amazon Mechanical Turk is a program that could potentially be used to inexpensively pre-screen and extract data for meta-analyses[58,59], which the team plan to utilise as well. Also, Aim 3.1 will develop AI-assisted technologies that semi-automate screening and data extraction, speeding up the relevant processes.

**AIM 3: Building new workflows & standards to support reliable evidence**

***Significance for Aim 3:*** Meta-science is a young and bourgeoning interdisciplinary field with many new opportunities. In addition to concerns over science (e.g., 'replication crisis') and the motivation to improve science (e.g., 'credibility revolution'), two major reasons exist for the current expansion of meta-science: 1) an unprecedented growth of the scientific literature (~3.3 million articles in 2020 alone; *Scopus*) and 2) technological developments enabling us to study the literature more effectively (e.g., text-mining and natural language processing assisted by AI).

This growth in publications and technologies, however, has not concomitantly come with increased reliability, due to the various ways research can be unreplicable. Therefore, the timing seems perfect for developing a computational workflow to accelerate meta-science and research synthesis. But how can we best create such methods? Furthermore, it is important to realise that promoting reliable science requires more than revealing the current gaps and biases (i.e., Aim 1 & 2). Then, what are the concrete ways to facilitate reliable science in the field of ecology and evolution, or in any field?

***Innovation & Activities for Aim 3:*** The CERC team will address these issues by using three team-science-based approaches: 1) *Meta-research And Research Synthesis* (MARS) *Hackathon,* 2) *modular pre-registration,* and 3) *Community-Driven and Dynamic* (CDD) *guidelines and best practices*.

**Meta-research And Research Synthesis (MARS) Hackathon** is where computer & statistical scientists and software engineers will be invited to work with biologists to create modules and improvements relevant to **research weaving** and especially for **AI-assisted semi-automation**. The team will use a similar model to the Evidence Synthesis Hackathon, which Dr. Nakagawa co-organised in 2019[28]. For this annual workshop, they will provide participant's stipends (partially covering travel-associated costs); this model will allow us to invite ~20 participants to work on developing computational tools for 5 days. Dr. Nakagawa will provide contributorship when relevant articles are published, so all contributors will receive fair recognition for their work. Academic contributors are often motivated to finish off and publish the project. Thus, Dr. Nakagawa will create a new MARS Hackathon community to continue the collaborations after an event. Assisted by hackathon events, the team will:

**Aim 3.1:** *Computationally implement a novel research weaving method and semi-automate for parts of research synthesis to support 'living' mapping of evidence (cf. Fig 3).*

**Modular pre-registration** is a new system to encourage researchers to register a study before starting the study. Registration can reduce artifactual results due to questionable research practices[47]. Also, it can mitigate publication bias; indeed, 60% of registered studies found null results compared to 10% of non-registered studies[60]. A typical registration would include three main parts: research aims (including questions & hypotheses, where relevant), a study design plan (e.g., sample size, data collection) and an analysis plan (e.g., statistical models)[47]. A full (pre-)registration shifts the burden of some work, such as analysis design, to earlier in a project, and this front-loading may be an obstacle to adoption for many. Therefore, Dr. Nakagawa proposes to lower the hurdle for embarking on registration to:

**Aim 3.2:** *Build the very first modular registration system to spread the culture of registration across the evolutionary and ecological community.*

This novel system will allow scientists to sequentially register the three different parts of preregistration (aims, plan and analysis) and allow updates. Also, the system will enable them to register just their aims, bolstering registration. The CERC team and a steering committee of *EcoEvoRxiv* will oversee the system, but Dr. Nakagawa will additionally involve many ECRs.

**Community-Driven and Dynamic (CDD) guidelines and best practices** are where practice guidelines are created and updated through inputs from stakeholder communities. Such community buy-ins are essential for researchers to take up guidelines and best practise that are shown to significantly reduce poor reporting[23]. Dr Nakagawa's lab has recently created the Preferred Reporting Items for Systematic reviews and Meta-Analyses for Ecology and Evolution (PRISMA-EcoEvo)[61] with the original authors of PRISMA[62,63] (cited >100,000 times). Via this protocol, his lab has developed a collaborative way of creating a guideline with a research community of 208 meta-analysts). In this way, the community will take up such a guideline as they own it. Based on this, the CERC team will form a community including expert groups to:

**Aim 3.3:** *Produce reviews and guidelines for research synthesis to encourage best practices in ecology, evolution, and related fields (e.g., updating meta-analyses), and expand this process to empirical studies.*

***Methodology for Aim 3:*** For **Aim 3.1,** Dr Nakagawa proposes to work on the implementation of research weaving as a dedicated software package, named *Rweaver*, in a free platform, *R*. This package will contain a set of functions for bibliometric & mapping processes, visualizations of key maps and webs (**Fig 1**). The CERC team will also use *Shiny R*, or similar alternatives, to create interactive interfaces as in Dr Nakagawa's earlier packages such as *squid*[64]. With MARS Hackathons, the CERC team will also semi-automate parts of the systematic review process[34,65,66], e.g., 'classification of papers', using deep learning methods and semi-automated extraction of relevant variables.

**Aim 3.2** will create a registry for ecology and evolution, tentatively, called '*EcoEvo Registry*', following the success of the free preprint server, *EcoEvoRxiv* (which Dr Nakagawa established). This registry will be created in a collaboration with Janeway (a publishing company, part of Birkbeck University of London) and the California Digital Library (CDL, part of University of California). Dr Nakagawa has already discussed this with Justin Gonder (Senior Production Manager, CDL), who is interested in potentially incorporating *EcoEvo Registry* as a part of the CDL collection (i.e., free of charge) in the future. Therefore, this plan is sustainable long-term beyond the life of the CERC.

**Aim 3.3** will create the next generation of guidelines and best practices (cf. Dr Nakagawa's earlier guidelines[13,67,68] through forming a working group for CDD guidelines and best practices. For example, the CERC team will create best practices for updating a meta-analysis (systematic review) and how to assess a meta-analysis (cf. Aim 1.1) for biologists, involving Delphi-type workshops[69]. In biological sciences, updating a meta-analysis is still relatively rare[70,71], but such updating should become more common in the future because meta-analyses have become a routine tool for synthesis. Once these example guidelines are successful, the team will continue to expand guidelines to primary studies and create templates for (pre-)registration using the CDD method.

**AIM 4: Developing new methods for meta-analyses and meta-meta-analyses: data recycling**

***Significance for Aim 4:*** The introduction of meta-analysis – a quantitative method to synthesize research – in the mid-1970s, was a scientific breakthrough[72,73]. It has changed the way scientists summarize research topics in medical, social, and biological sciences – having a major impact on the way policymakers make decisions using available evidence. In 2018, Dr Nakagawa and his colleagues published a *Nature* article to celebrate the 40-year contribution of meta-analysis, showing how research synthesis has become an integral part of scientific progress[71]. However, their work has also pointed out, at least, two future opportunities: 1) with an ever-increasing number of meta-analyses, there will be much scope for 2nd order meta-analyses (meta-meta-analysis) and 2) many of current meta-analyses focus on comparing means of two groups, neglecting other statistical parameters (e.g., variance), which can be meta-analysed.

Relating to the second point, the current SGBA+ (*Sex or Gender-Based Analysis plus*) also exclusively focus on comparing average (mean) differences between sexes or genders. The case in point is that *Nature*'s 150th-year anniversary collection published in 2019 included a guide for how to analyse sex as a biological variable, yet it solely concentrated on mean differences[74]. Such obsession with means can be attributed to our statistical tools[75]. Indeed, with the common tools, it is not obvious how to compare other aspects of sex differences such as variance, covariance, skewness, and kurtosis, although these statistics can enable new and hidden insights into sex differences. For example, changes in the shape of trait distributions and their associations can indicate the history of natural & sexual selection[76,77], comorbidity, and extreme & rare cases of diseases[78,79]. Although Dr Nakagawa has developed a new effect size statistic to compare variances between two groups [80], there are no formal meta-analytic methods to compare differences in covariance, skewness, and kurtosis.

***Innovation & Activities for Aim 4:*** To exploit the above opportunities and to resolve the issues, Dr. Nakagawa will innovate and extend meta-analytic methods for 1) **individual participant data, IPD** (i.e., raw/original data) and 2) **meta-meta-analysis**, and demonstrate their use, as an example, by applying them to datasets and meta-analysis on sex differences, respectively.

**IPD meta-analysis**: In medicine, the use of IPD meta-analysis is becoming a new gold standard[81], although such use is still limited in the field of social and biological sciences including ecology and evolution. IPD meta-analyses have the benefit of being able to standardise each original dataset, which cannot be done if one is using summary statistics from a publication. Therefore, IPD meta-analyses can improve the reliability of traditional meta-analyses (e.g., comparing means, slopes, survival %, time-to-event). Currently, given poor reporting[82], IPD meta-analyses seem like the only practical route for comparing covariances, skewness and kurtosis between two groups. Furthermore, Dr Nakagawa's group has recently shown that a typical empirical paper (study) would be mostly underpowered to detect differences in variances between two groups[19] due to its relatively small sample size. The only practical way is to use meta-analysis. The same thing can be said for the statistical parameters such as covariances (2nd moment), skewness (3rd moment) and kurtosis (4th moment); one requires larger and larger sample sizes as the moment increases. Therefore, Dr. Nakagawa proposes to:

**Aim 4.1:** *Develop, implement, and validate a new set of effect sizes for comparing differences in co-variance, skewness, and kurtosis between two groups (e.g., females vs. males, treatment vs control).*

Meta-analyses of comparing covariance, skewness and kurtosis will open new directions in studies of sex differences and help, for example, understanding sex differences in co-selection of traits, disease comorbidity and sex-biased diseases[78,79]. Further, as the CERC team develop and validate new methods in Aim 4.1, they will also:

**Aim 4.2:** *Apply these new methods to large individual-level datasets to demonstrate the power of the extended SGBA+ methods and new questions and insights that can be asked and gained.*

Two examples of individual-based datasets are: 1) SPI-Birds Network and Databases[83] and 2) International Mouse Phenotyping Consortium (IMPC)[84]. These datasets are complementary as SPI-Birds provides individual data for natural populations across 19 species of birds while IMPC gives us high-resolution individual data of one species (i.e., mice).

SPI-Birds: This network was officially launched in 2020 with > 120 members, including Dr. Nakagawa's lab, (21 countries) monitoring over 80 populations of 19 species; within these, data on > 1.5 million individual birds (from 2,000 culminative years), and counting. The database holds basic morphological data, life history data (e.g., phenological data) and reproductive success (i.e., fitness) for all the species over multiple years. SPI-Birds is currently comprised primarily of European study populations. Dr. Mathot (core team member) has recently added her North American population to the database, and together, Dr. Nakagawa and Dr. Mathot will work to identify other study populations from around the world that can be added to increase global representation.

IMPC: This database consists of > 5 million measurements of phenotypic data from over 100,000 mice from 12 different centres, and expanding; the database includes over 500 traits from 9 functional groups (physiology, morphology, metabolism, immunology, hematology, heart functioning, hearing functioning, eye functioning and behaviour)[84]. Working with IMPC bioinformaticians, Dr Nakagawa's lab has used this database to quantify and publish an *eLife* paper on sex difference in variance[85] and a preprint on sex difference in allometry[86] (currently reviewed at *Nat Comm*).

**Meta-meta-analysis** (2nd order meta-analysis): it aggregates meta-analyses instead of primary studies. Yet, conceptually, a 2nd order meta-analysis is akin to conducting a very-large-scale (1st order) meta-analysis, allowing us to synthesize and explain variation found between meta-analyses (as well as primary studies). At the same time, meta-meta-analysis can be used as a tool for meta-research because we can not only quantitatively assess the quality of each meta-analysis, but we also can quantitatively aggregate the extent of publication bias (e.g., small-study effect and decline effect)[87] and across different meta-analyses, as we have done our recent work[19]. Although, statistical procedures for both 1st and 2nd order meta-analyses are almost identical there are unique methodological issues that have not been yet addressed fully for 2nd order meta-analyses. Two notable issues are 1) many meta-analyses may overlap in terms of included primary studies (i.e., non-independence issue) and 2) also meta-analytic estimates are often subjected to publication bias (i.e., inflated overall effect). Given this, Dr. Nakagawa proposes to:

**Aim 4.3:** *Develop a robust and general method for 'meta-meta-analysis' and apply it to meta-analyses on sex differences and make this project the first-ever 'living' meta-meta-analysis.*

This meta-meta-analysis will quantify our current understanding of sex differences (and similarities) and potential publication biases in current meta-analyses. This aim will also assess the reporting and conduct quality of each meta-analysis (see below). Therefore, it will elucidate knowledge clusters, gaps, reliability, and biases, where we can focus attention, and guide future studies.

***Methodology for Aim 4*:** Simulation will be used to validate new statistical methods via the *Mote Carlo* method in the *R* environment, as used in earlier Dr Nakagawa's simulation studies[88-90]. Choice of parameter space (e.g., sample sizes, the strength of correlations) will be based on empirical work like his group did earlier[89,90]. In simulation, the CERC team will consider both independent and non-independent two group cases. The team will implement these approaches (from **Aim 4.1 & 4.3**) using IMPC and SPI-Bird data with different *R* packages, such as *MCMCglmm*[91], *metafor*[92], *brms*[93], and *greta*[94]. The new package *greta* uses TensorFlow's fast computation and *Hamiltonian Monte Carlo*[95]. A Hamiltonian algorithm is also implanted in *STAN*[96], which provides a powerful and flexible Bayesian statistical framework; an emerging package, *brms*, uses *STAN* via *R*.

The notable merit of IMPC database is in having >11,000 both males and females (~ 50:50%) that have been measured for more than 300 traits (each trait has more than 50 males and females). On the other hand, SPI-Bird dataset comprises 19 different species, which will call for phylogenetic meta-analysis, whose importance has been shown by our recent simulation study[90]. Both datasets will be perfect for showcasing the power of new meta-analytic methods.

**Aim 4.3** will make our 2$^{nd}$ order syntheses into a *living* (continuously updated) review of reviews[30,31]. As with Aim 1.2, the CERC team will set up a web platform for this living meta-meta-analysis (see **Fig 3**). On this platform, the team will recruit researchers who are going to conduct a meta-analysis on sex differences in any trait to be a part of the open community. The recruitment process will be facilitated by a bibliometric map of collaboration networks, considering EDI (c.f., **Aim 1.1)**.

## 2) ALIGNMENT WITH SCIENCE, TECHNOLOGY AND INNOVATION PRIORITIES

This program will contribute to a range of the *CERC's Science, Technology, and Innovation (STI) Priorities* by making the foundational field of ecology and evolutionary biology more trustworthy and inclusive via normalizing open and team science and developing statistical and computational infrastructure, useful not only for scientists but also for members of the public. Indeed, the proposed CERC program is well aligned with all the five grand challenges of STI Priorities.

**Technologically Advanced Canada:** The program addresses the two Objectives: "*Develop enabling and digital technologies and leverage disruption to support innovation*" and "*Advance knowledge on public acceptance and adoption of new technologies*" by leveraging the two areas of focus: *Artificial Intelligence* and *Big Data Technologies and Analytics*. One of the main and scalable outcomes is a disrupting innovation of the AI-based semi-automated pipeline for research (literature) synthesis and continuously updated or '*living*' reviews, which can be used for a wide range of fields including biological, social, and medical sciences. Further, as Dr. Nakagawa and colleagues wrote in a review in *Nature* that "*Meta-analysis is the grandmother of the 'big data' and 'open science' movements*"; the program further develops meta-analytic methods so that big and open data can be utilised more effectively (Aim 3.1) The program's effort to increase public acceptance of ecological and evolutionary evidence via *Big Data Technologies and Analytics* (e.g., Aim 1.2 & 4.3) itself promotes the acceptance of technologies at the same time. Therefore, the program will aid in "*Advancing transformative and enabling technologies that will support a technologically advanced economy and society*".

**Sustainable Food Systems and Clean and Resource-Rich Canada:** The CERC program is clearly relevant to these two grand challenges, especially to the two following areas of focus: 'Climate change research' and 'Conservation ecology'. One of the proposed activities (Aim 1.2) will create an 'open synthesis community' which will investigate climate change via world-wide monitoring of contemporary changes in selection in animals and plants (including anthropogenic impacts). Such monitoring not only informs agriculture but also conservation biology, contributing to these two priorities. In addition, this activity can also inform the other two areas of focus: 'Agri- & aqua-culture' and 'Plant health'. Importantly, the program not only produce relevant meta-analyses, but also train many researchers in evidence-based synthesis with partnerships with, for example, Alberta Environment and Park, Alberta Conservation Association, and Environment Canada and Climate Change (Aim 2.3). Therefore, the program will build enhanced capacity for evidence-based syntheses and actions in government agencies and not-for-profit organisations in Canada, positively influencing effective policymaking and decisions in relevant areas, and contributing to *"Enhance resiliency to the adverse effects of climate change (adaptation)"*, preparing for the challenging future ahead.

**Healthy Canadians:** Through promoting scientific trust and evolutionary thinking, the CERC program addresses the Objective; "*Support Canada's readiness for health emergencies*". Evolutionary thinking could enormously benefit 'Population and Public Health'; for example, it will enable people to make informed decisions on both human (e.g., vaccination) and environmental health weighing trade-offs – one of the central concepts of both ecology and evolution, Furthermore, the development of new meta-analytic methods and their application, for example, to the issue of sex differences. contributes to the areas of focus: *Precision Medicine* as the proposed activates (Aim 4.2-4.3) will elucidate neglected aspects of sex (or gender) differences as well as similarities. Taken together, the program could significantly contribute to "*Enhancing the health and wellness of Canadians across all life stages*".

**Innovative and Resilient Communities:** This program directly addresses the Objective "*Improve and strengthen public institutions and public trust*" by tapping into six areas of focus: 1) *Data*, 2) *Governance and Public Institutions*, 3) *Healthy communities*, 4) *Inclusive growth*, 5) *Inclusive societies* and 6) *Technological solutions*. First, the program will use open '*Data*', '*Data'* synthesis, '*Data'* recycling and cutting-edge '*Technological solutions*' to build public trust in ecology and evolution, and broadcast the critical importance of evolutionary thinking (supporting '*Governance and public institutions*').

For example, evolutionary biology has proven to be indispensable in tracking the evolution of COVID-19; the emergence of variants is a natural evolutionary process. Therefore, normalizing evolutionary thinking downstream will result in safe and '*Health Communities*'. Our outreach activities and platforms democratise ecological and evolutionary evidence creating '*Inclusive Societies'* and promoting '*Inclusive Growth'*. Especially, the program's two activities (Aim 1.2 & 1.3) involving high schoolers and Indigenous communities are examples of such inclusivity and facilitating evolutionary thinking from the bottom up, contributing to "*Building thriving communities that are inclusive, liveable, smart and safe*".

Dr. Nakagawa has a track record of already contributing to all aspects of *CERC's STI Priorities*, and many areas of focus within these priorities. Therefore, this CERC program can become conduits between other CERC programs, potentially connecting and leveraging many other CERC initiatives.

### 3) PROMISE OF THE PROPOSED RESEARCH FOR THE CHAIR IN THE GLOBAL CONTEXT

**Promises:** The project's Aim 1 & 2 activities (i.e., research synthesis and replication prediction) will map evidence, confidence, and validity of scientific results **–** illuminating gaps, clusters, and biases in evolutionary ecology. Therefore, they will lead to new knowledge with increased levels of veracity and thus direct the future of the field, for example, where to focus our research efforts, accelerating the progress of the field. Further, implementing *research weaving* and semi-automating AI-assisted synthesis processes (e.g., technologies for a living review) will provide scalable tools for many projects beyond the field of ecology and evolutionary biology (Aim 3.1). Importantly, these activities along with the modular (pre-)registration platform (Aim 3.2) will also improve research efficacy (e.g., by reducing unpublished work, poor reporting, artifactual results). Creating best practices and guidelines for research synthesis in ecology and evolution (Aim 3.3) will facilitate a better quality of research synthesis, increasing the robustness of review-based evidence. Furthermore, the proposed new meta-analytic methodologies and their implementations (Aim 4) will not only change the way researchers investigate sex, gender, or other differences between groups, but also lead to many new questions and intellectual challenges in biological, (bio-)medical, and social sciences. *Taken together, this CERC program is likely to revolutionise how ecological and evolutionary research is done by placing team and open science at the core of the field and developing a new networked global community of engaged and trained researchers.* This program will use a new means to achieve open and team science (e.g., open synthesis community, CIMPs, DEAR workshops), which can be adopted in many different fields, therefore, spreading the impact of this CERC program far beyond ecology and evolution.

**Global contexts:** The quality control of systematic reviews (meta-analyses) have been greatly aided by two organisations, *Cochrane*, in medical sciences and *the Campbell Collaboration* in social sciences. More relevantly, we have *the Collaboration for Environmental Evidence, CEE* (of which Canadian Centre for Evidence-based Conservation, CCEC, is part) which oversees systematic reviews in environmental sciences. Furthermore, there are organisations, which focus on research synthesis in a more board sense such as *Conservation Evidence* (Cambridge), *iDiv* (German Centre for Integrative Biodiversity Research, Leipzig, Germany) and *NCEAS* (National Center for Ecology and Analysis and Synthesis, US). This CERC program plans to establish collaborative relationships (e.g., co-hosting workshops) with all the three centers as well as with *CEE*. There is no synthesis center especially the center to oversee systematic reviews (meta-analyses) in ecology and evolution (note *CEE* does cover applied topics in ecology). The proposed CERC program fills this gap. For meta-science, which is relatively a young field, the Centre for Open Science (US) and METRICS (METa-Research Innovation Centre at Stanford) were established in 2013 and 2014 respectively. More recently, several organisations such as METRIC-Berlin, the Research-on-Research Institutes (UK-Netherlands) and the QUEST Center for Responsible Research (Germany), has opened. These institutes and initiatives are predominately led and organised by medical and social scientists. The proposed CERC program fits in this international ecosystem while filling this gap. Importantly, the program will create considerable new international collaborations by expanding the existing research network, Dr. Nakagawa has built and liaising with societies some of which Dr Nakagawa has co-established or is part. The proposed CERC program is unique combining these two major areas: research synthesis (meta-analysis) and meta-science. The program will become an international hub for: 1) meta-science in evolutionary ecology and related fields promoting open, transparent, and reproducible science, and 2) research synthesis, creating high-quality systematic reviews (meta-analyses) in ecology and evolution, and providing training in research synthesis. Furthermore, the program will lead to scale-able infrastructure in two forms by: A) building up computational and AI-based methodologies for meta-research and research synthesis including qualitative synthesis and B) developing statistical and simulation methodologies for meta-analysis and quantitative synthesis. These methodological developments will be facilitated by a cross-disciplinary team and collaborators (e.g., computer scientists and statisticians) and the outcomes of such developments can and will be applied to a wide range of fields.

**4) RESEARCH COMMUNICATIONS, MOBILIZATION AND TRANSLATION**

In addition to traditional academic communications (e.g., publishing in top journals, presenting at conferences & creating open-source software; see Section A), this CERC program will build two major communication channels to connect academics, members of the public, and other stakeholders (i.e. government and not-for-profit organisations). First, the program will create a dedicated website for this program and make it a unique nexus for reaching other researchers and the public. This website will connect all the proposed activities and resulting communities. Therefore, this website will be designed to become a permanent '*communication & knowledge exchange*' channel for both ecologists and evolutionary biologists to meet, discuss and continuously better the field. Furthermore, this website will also be a nexus for open, transparent, and reproducible science working with learned societies such as SORTEE (the Society for Open, Reliable, and Transparent Ecology and Evolutionary biology) and AIMOS (the Association for Interdisciplinary Meta-Research and Open Science), in which Dr Nakagawa has been closely involved. All studies will be registered where feasible, especially using the proposed new system *EcoEvo Registry* and preprinted via *EcoEvoRxiv* and *bioRxiv*; this CERC program is committed to making their science as open as it can be so that the program itself will become an excellent exemplar of open science and transparent practice. *Second*, the program will set up a special CERC outreach team that will coordinate school visits (e.g., Aim 1.2 & 1.3), engaging students into our program that will form a global network of scientists and working with Indigenous communities to create educational materials. Such school visits and engagements with students and indigenous communities, enhancing their appreciation of STEM and inspiring their career paths more into STEM subjects. Also, this outreach team will work closely with an excellent media team at the host institution's team *at Media Relations and Contacts* to utilize their connections and capability to communicate the Canadian public and government (see also Section F).

Furthermore, as knowledge communication and translation are fully integrated within the CERC program, it will build capacity, which empowers researchers, especially ECRs. They come at least in 4 interrelated forms. *First,* the program will build two new communities: 1) a community participating in *Replicating EcoEvo* (Aim 2.1 & 2.2), and 2) an open synthesis community contributing to 'living' synthesis on natural selection (Aim 1.2). It is expected at least 300 scientists will be involved in each community. '*Replicating EcoEvo Community*' will increase capacity for how to evaluate research effectively. '*Open Synthesis for Natural Selection Community*' (Aim 2.2) will be used as a model for other topics in ecology and evolution. *Second,* via DEAR Workshops (Aim 2.3) and other actives, the program will train >250 ECRs in research synthesis, increasing capability and collegiality of the scientific community, nationally and internationally. MARS Hackathons (Aim 3.1) will enhance collaborations between the fields of biology and computer sciences, enabling cross-fertilization between fields, which will grow the interdisciplinary capacity to face complex future challenges. *Third,* this program will bolster capacity for carrying out higher quality and reliable science, by implementing *EcoEvo Registry* and CDD (Community-Driven and Dynamic) guidelines and best practices. *Fourth,* activities in Aim 1 can act as a starting point for an ecological and evolutionary version of a community akin to Cochrane and the Campbell Collaboration that coordinate thousands of researchers to provide the best and up-to-date evidence on a range of health, social and societal issues. Such a community can also facilitate decisions on what new meta-analyses, or primary studies, should be undertaken and which existing meta-analyses should be updated. The program will aim to set up '*The Collaboration for Ecology and Evolution'*. Such a collaborative initiative will be an enduring legacy of this CERC program.

**5) FILLING A GAP AND COMPLEMENTARITIES**

**Host institution:** The UofA is internationally recognised in both fields, 'Ecology & Evolution' and 'Artificial Intelligence, AI' (see Section B). Yet, there is no individual who strongly connect these two fields. Dr. Nakagawa will become a conduit between the two areas at the UofA. Such a new connection will create an internationally unique yet much needed collaborative among ecologists, evolutionary biologists, and computer scientists. Dr Nakagawa's research is exceptionally cross-disciplinary, and he has been bridging different fields for several years by transporting and exchanging ideas and insights from different fields (especially, ecology, evolution, statistics, computer sciences, psychology, and biomedicine) and collaborating over 750 scientists (see Section A). Importantly, the proposed CERC program intersect with four of the five *signature areas* of the host institutions: 1) AI4Society, 2) Precision Health, 3) Research at the Intersections of Gender, and 4) Situated Knowledges: Indigenous Peoples and Place. These 4 signature areas well aligned with all of the five *CERC's Science, Technology, and Innovation Priorities* (listed above). Also, Dr. Nakagawa will become a champion of open and reproducibility science at the UofA, connecting all existing advocates of open science movements at the host institution, scattered across different faculties. Further, the CERC program will, for example, bolster the UofA's campaign for trust in science, spearheaded by Dr Tim Caulfield (core team member).

**Canada (the national context):** Although several open science and meta-science initiatives exist in Canada, such as the Centre of Jounralology (Ottawa Hospital), Tanenbaum Open Science Institute (TOSI; Montreal Neurological Institute) and the Living Data Project (Canadian Institute of Ecology and Evolution), Canada currently lags other countries in these fields. For example, the UK Reproducibility Network (UKRN), funded in 2015 and including over 25 universities, is a peer-led consortium for improving and supporting rigour and reducibility in research by providing training, peer-support, and infrastructure at the local and national level. Similarly, there is a new US initiative, the Higher Education Leadership Initiative for Open Scholarship (HELIOS), which includes 75 US universities and the Center of Open Science, established in 2013, has been leading in open and reproducibility science in terms of research and training. There has been a movement led by Drs Robert Thibault (Sandford) and David Moher (Ottawa) to create the Canadian Reproducibility Network so that different Canadian institutions can cooperate to improve research quality and reproducibility in a concerted manner. Dr Nakagawa plans to work with Drs Thibault and Moher to establish and build such a network in Canada. Of relevance, Dr Nakagawa is a founding member of the Australian Reproducibility Network. In addition, Dr Nakagawa has co-founded an international society, SORTEE and was an executive member of another international society, AIMOS. Notably, supporting open science will lead to many EDI benefits such as equitable and democratization of knowledge and a national-level concerned effort is required to make open science inclusive so that everybody has access to training, peer-support, and relevant infrastructure.

In terms of research synthesis, the CERC will work closely with Canadian Centre for Evidence-based Conservation (CCEC; directed by Dr Steven Cooke). While CCEC focuses on research synthesis on applied and practical issues, the CERC program will focus on synthesizing more fundamental issues. The CERC team can also undertake syntheses of cross-disciplinary nature. Many pressing issues of our time transcend disciplinary boundaries (e.g., climate change, sustainability, and gender/sex differences), yet a large gap currently exist for such interdisciplinary syntheses in the literature at large.

**6) EQUITY, DIVERSITY, AND INCLUSIVENESS CONSIDERATIONS IN RESEARCH PROCESS**

The field of ecology and evolution embraces the study of diversity as a field, and one of the most important questions in the field is understanding the diversity of life. Yet, as a field, there is so much room for improvement in terms of EDI[97]. The proposed project embeds EDI considerations in all aspects of research: *Questions, Design, Methodology, Data Collection, Analysis & Interpretation,* and *Dissemination*. Such consideration in the proposed program is especially notable in design, methodology and dissemination. For example, the CERC program is *Designed* to create an 'open synthesis community' that, in its nature, promotes EDI. This is because of three reasons, mentioned above: 1) improving research efficacy by inclusive data collection and archiving 2) increasing diversity in participation and reducing inequality in research opportunities, and 3) enabling syntheses to stay up to date, because a diverse group of researchers upload their own results and they all will be fairly rewarded with contributorship[29]. Also, in creating such communities (e.g., *Replicating EcoEvo Community*, *Open Synthesis for Natural Selection Community*'), the CERC program will use its strength in quantitative skills in tracking diversity and actively recruit a diverse group of people (e.g., one can combine bibliometric information and network analysis to search and find relevant experts cf. Fig 1). Using a survey method, this program will target actively recruiting historically marginalised groups (in terms of gender, sexual orientation, ethnicity, etc.) to grapple with implicit and explicit gatekeeping. Notably, the CERC team will pay special attention to the development of AI-assisted semi-automation, as AI models could create more inequities[98]. The team will mitigate this potential issue by several tests and validations; for example, both sexes are equally represented in the proposed AI-assisted tools.

In terms of *Methodology*, *Analysis & Interpretation*, and *Dissemination*, this CERC program will take SGBA+ (*Sex or Gender-Based Analysis plus*) to the next level via creating a new set of statistical methods to investigate sex (and gender for human studies) differences and similarities (Aim 4). Although there are guidelines for both reporting and analysis for studies including sex as a biological variable [74,99,100], these guidelines often lack statistical details. For example, Sex And Gender Equality in Research (SAGER) reporting guidelines do not mention (co-)variance, skewness, and kurtosis[99]. Therefore, CERC team will need to revisit reporting guidelines again collaborating with leading scientists and advocates of the study of sex (or gender) differences as well as statistical/methodological experts. Furthermore, many analysis guidelines do not come with easy-to-follow statistical implementations, which is a clear current gap that Aim 4 will also fill. Indeed, Dr Nakagawa's group has not only developed many methodologies in the past but also implemented these methods by producing open and freely accessible *R* packages. The CERC team will develop an analysis pipeline and implement it as *R* packages (with *R* Shiny interfaces for wider accessibility) for the proposed methods to analyse sex (or gender) differences. These activities can bring about major advances in SGBA+, changing the way data are analysed and interpreted, casting a new light to this neglected aspect. In addition, as mentioned in Section A, Dr Nakagawa will plan to embed EDI considerations into recruiting and training of the CERC team so that the whole team embraces the EDI philosophy into their research.

**7) CO-CREATING RESEARCH WITH FIRST NATIONS, INUIT AND MÉTIS PEOPLES**

The research program was not co-created with Indigenous peoples, but will consult and engage with Indigenous peoples in creating educational materials for high school students (Aim 1.3). The team will map Canadian high school curriculum for evolutionary biology and survey biology teachers how evolutionary biology is taught and how students understand and apply evolutionary thinking. The CERC team will be guided by the core team member and educator Dr. Marc Higgins, who has worked on science curriculum development and pedagogical delivery in over 50 reserve and urban Indigenous communities. Dr. Higgins will assist in designing and delivering classrooms-based interviews and questionnaires, and building relationships with Indigenous communities. The team will work with Indigenous teachers, and local evolutionary biologists/ecologists to create education materials for evolutionary biology/ecology using local examples. Evolutionary thinking and associated concepts are sometimes compatible with Indigenous peoples' cultural values[101] although such connections are rarely recognised. Establishing educational materials that highlight complementarities between evolutionary thinking and Indigenous ways of knowing will provide opportunities to co-create curriculum that is culturally relevant for Indigenous students, providing opportunities for bi-directional learning and communication between Indigenous and non-Indigenous students.

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