Executive summary
Species invasions are widespread in human-dominated landscapes, where large economic costs are often incurred due to altered ecosystem services, impacts on human health, and from control efforts. Frameworks, concepts and paradigms for understanding and managing invasions are based largely on insights from natural habitats, yet urban ecosystems differ radically in that the environmental impacts of human activity are detrimental for many species and so maintaining native biodiversity and the ecosystem services that benefit people in cities can be difficult and expensive. This proposal argues for the creation of a Global Urban Biological Invasions Consortium (GUBIC) to oversee a network of projects and collaborations to determine the magnitude of invasion economic and ecosystem impacts in cities around the world. The main objectives of this consortium and this funding proposal are: 1) to assess the influence of urban to rural gradients in human impact, economics, and environment within cities on invasive species population sizes and diversity; 2) to determine how political, economic, trade, and environmental differences among cities influence the invasibility of cities; 3) to quantify ecosystem service and disservice provided by non-native species within and among cities; and 4) to evaluate invasive species urban policy and management decision triggers in different socio-economic conditions. This funding will support a number of activities, including a symposium, a number of workshops and collaborative meetings, postdoctoral, graduate and undergraduate research training, and engagement with non-academic partners.

Solving the global urban biological invasions conundrum

The study of biological invasions has focused largely on the spread and impact of non-indigenous species (NIS) in natural and semi-natural habitats. Yet, invasions are also widespread in human-dominated landscapes, where large economic costs are often incurred due to altered ecosystem services, impacts on human health, and from control efforts. Urban habitats represent the ultimate apex of human modification of the natural ecological and geological processes that structure a given locale. Frameworks, concepts and paradigms for understanding and managing invasions are based largely on insights from natural and semi-natural systems, yet urban ecosystems differ radically from (semi)natural systems in that the environmental impacts of human activity are detrimental for many species and so maintaining native biodiversity and the ecosystem services that benefit people in cities can be difficult and expensive.

This proposal argues for the creation of a Global Urban Biological Invasions Consortium (GUBIC) to oversee a network of projects and collaborations to determine the magnitude of invasion economic and ecosystem impacts in cities around the world. The reasons why this work is so critical at this juncture is fourfold: 1) Greater numbers of people live in cities than at any other time in our history and so the well-being of cities directly impacts the health and happiness of people; 2) trade and the movement of people in and out of cities has resulted in unprecedented movement of species to urban areas outside of their native ranges; 3) pest outbreaks and species invasions have resulted in massive economic costs and environmental degradation –take for example the impacts of the emerald ash borer and dog strangling vine in Toronto; and 4) there is currently widespread misunderstanding of the potential threats invasive species pose and that existing invasive species management frameworks are not well suited to managing invasive species in urban areas, where human perception, well-being and culture influence what kinds of species persist. The main objectives of this consortium and this funding proposal are: **1) to assess the influence of urban to rural gradients in human impact, economics, and environment within cities on invasive species population sizes and diversity; 2) to determine how political, economic, trade, and environmental differences among cities influence the invasibility of cities; 3) to quantify ecosystem service and disservice provided by non-native species within and among cities; and 4) to evaluate invasive species urban policy and management decision triggers in different socio-economic conditions**.

Some authors argue that we may have to tolerate NIS in certain situations; NIS may perform better than natives in urban areas simply because species that happen to be pre-adapted to urban conditions tend to get moved to other cities. Yet, the inclusion of pre-adapted NIS into urban areas introduces a number of complicating factors: 1) these urban NIS may create, enhance or restore the delivery of ecosystem services in areas that may be under-performing because of a lack of suitable native biodiversity or due to elimination of, or reduction in, such services due to human activities (for example floral resources for pollinators [1]); 2) however, urban areas may provide a beachhead for new NIS that subsequently invade nearby intact habitats [2, 3]; 3) and the presence of NIS in urban areas may trigger management response if they are listed as noxious or controlled species because of impacts elsewhere; and 4) cultural beliefs and values might support the presence of some NIS but not others, independent of potential ecological threats.

These four complicating factors are seldom an issue for the management of NIS in natural habitats but are creating growing problems for policy and natural resource managers in urban

areas. Invasion of NIS into protected natural areas usually elicits a clear response based upon a widely accepted understanding and policies supporting the role of protected areas in conserving native biodiversity. Given that urban habitats supply unique opportunities for NIS and that human-organism interactions are acute and mutually shape each other's urban experience, is it worth asking whether biological invasions in urbanized areas require a unique paradigm. Currently policies that govern urban responses to NIS invasions are most commonly developed or implemented at regional, provincial/state, or national levels, and usually do not take into account ecological, economic or social drivers in urban habitats. In response to these complicating factors urban invasion management frameworks have recently been developed [4, 5], but these have not been widely evaluated.

Invasions in urban areas are mediated by the same basic ecological processes that affect all species: environmental influences on fitness, interspecific competition, infectious diseases, etc. However, the magnitude of effect and relative importance of some mechanisms are greatly altered in urban areas. It is widely appreciated that cities create a 'heat island' effect [6] that affects many species, for example by increasing thermal stress. Less well known are many other environmental consequences of cities - from altered water flow regimes to high nutrient deposition, and compaction and denudation of soils. Thus, this combination of stressful environmental conditions along with the loss of native habitats has resulted in the emergence of a novel ecosystem type [7]**,** which tends to be more stressful for many organisms and selects for species with specific traits that allow them to cope with these stresses [8]. At the same time, biological interactions are also influenced by urbanization. Negative interactions that would normally limit species' population growth and spread into new habitats, like competition and predation, are likely substantially different in urban habitats compared to natural ones. However, the direction and magnitude of these modified interactions is likely highly context- and taxa specific. This context dependency comes from the fact that human activities and forms of habitat modification are quite heterogeneous in urban areas. As an illustrative example, riparian forests might be structured by semi-natural processes, where competition is a dominant mechanism which limits NIS invasion, yet a few meters away gardeners purposefully reduce species competition, and these gardens are likely to host high NIS diversity [9]. Some taxa might experience reduced predation or herbivory in urban areas, but the opposite could be true for other species. Most urban areas around the world are currently hotbeds of mesopredators; introduced domestic cats are inflicting extremely high predation pressure on songbirds in urban areas [10].

Despite the fact that these environmental and ecological processes are likely to be extremely important for understanding NIS dynamics, the human well-being, cultural, and economic dimensions of cities cannot be overlooked. Human behavior and activity can strongly influence where non-native species establish populations and how they spread through landscapes. Further, human populations may value or benefit from the ecosystem services provided by non-native species. Each of these anthropogenic elements could either reinforce the need to control NIS, or alternatively provide arguments against NIS control [4]. None of these factors can be ignored when framing issues relating to NIS in cities since sustainable invasive species management requires that the citizenry and governments see invasion control as worthy expenditures that do not conflict with other values or priorities. It is difficult to predict when invasive control will be in conflict with human concerns, but it is clear that successful NIS management requires sociological analyses along with proactive community engagement and education.

A desperate need for information about urban invasions

There is some evidence that NIS richness increases with urbanization [11-13]. NIS success and diversity is influenced by many factors, and studies identify many causes for NIS urban success, including: high rates of species importation [14], reduced negative interactions like competition and predation [9], high resource availability [15], and altered environments, which favour NIS [12]. However, as noted in a recent review [16] it is currently impossible to disentangle these mechanisms and there are not enough studies that adequately assess the abundance and richness of NIS across gradients of urbanization. The main weakness that was identified was the gradient itself. The urban gradient is not synonymous with distance to urban centre, but rather should reflect landscapes immediately surrounding sampled sites. The majority of the studies that examine NIS in urban areas group sites into broad classes (e.g., urban, suburban, rural, etc.), which ignore among-site variation [but there are good examples to follow, e.g., 17]. The problem with this is that two sites categorized as, say, "suburban" might differ substantially in the composition of the area surrounding plots in terms of residential infrastructure, industrial activities, the number of size of roadways, the number of types of maintained parks, etc. More than just the influences of the physical structure of landscapes, the socio-economic spatial patterns in cities have important implications for biological diversity [18].

Thus, a standardized set of protocols and study design is desperately needed to adequately evaluate the relationship between urbanization and species invasions. A standardized framework can determine which aspects of urbanization appears to best favour a replacement of native species with NIS. Further, to fully understand the potential impacts of NIS on native species and the delivery of ecosystem services, we need to assess landscape and local influences on biodiversity and NIS performance.

Research objectives

The GUBIC research consortium will serve as a platform to understand urban influences on species invasion, the delivery of ecosystem services, and to develop guidelines for sound policy and management. There are many studies that examine NIS in urban areas, however, as pointed out by Cadotte et al. [16], the lack of standardization of how studies sample NIS and the scarcity of studies that actually quantify urbanization variables, means that developing a general understanding of urban impacts on NIS and ecosystem function is challenging. This reality makes it difficult to develop management and policy frameworks to deal with NIS in cities. To overcome this lack of general understanding, this funding will support four core activities:

1) Data synthesis: One of the workshops and the funded postdoc (who will be 50% supported by Prof. Cadotte's endowed TD Chair) and two PhD students (one from Toronto and one from South Africa) will compile data on urban NIS and native diversity within cities and ecoregions surrounding each city. Some cities have extensive datasets available, while others will need to be compiled from primary sources. The goal will be to quantify the effect of urbanization on biodiversity relative to background biodiversity levels. Geographical Information Systems (GIS) layers will be compiled for each city with layers of environmental, NDVI, human impact (e.g., impervious surface, roads, built structures, etc.), and socio-economic data. Composite maps of human impact and potential ecosystem services will be created. For cities where spatially explicit biodiversity and exotic species data are available, we will determine how human impact at several expanding radii around biodiversity sampling points. Ecosystem service contributions

from individual species will be estimated using available information, augmented with local observations. For regulating services, species trophic status of animal species and maximum height and growth rate of plants will be used to estimate carbon storage. For tree species, we estimate several regulating services, like pollution removal and temperature regulation using the iTree database. For supporting services, pollination resources of plants and trees will be estimated. For provisioning services, human use (food, medicinal, building, etc.) will be qualitatively assessed from existing literature and local knowledge. Finally, for cultural services, we will assess the values of exotic and native species by compiling nursery availability and potentially sales. Further, global climatic, environmental, economic, trade, and geographic variables will be collated to determine if cities result in homogenized biotic and if this driven by exotic species. Finally, widespread NIS, found in at least ten cities, will be selected for more detailed analysis and comparisons among cities. For these species, this work will examine how abundances are shaped by urban gradients across different cities. The relative importance of environmental and anthropogenic influences on their success will be determined. Data agreements are already in place to use data compiled by UrBioNet and additionally for more than 60 cities contributed by collaborators.

2) Forming environmentally sound policy for cities: The two other graduate students (again one from Toronto and one from South Africa) will compile examples of different policy frameworks from cities around the world. Their findings will form the basis of our second and third workshop on urban environmental policy that will include sociologists, geographers, policy experts and indigenous leaders. The goal will be to assess different forms of public engagement and inclusion, and to determine how NIS policies can be implemented in urban areas of differing environmental and socio-economic contexts.
3) Developing management frameworks: An important component will be to evaluate local management strategies and to assess the utility of a recently proposed invasion management framework. Existing frameworks will be discussed in the policy workshop. Assessing frameworks will utilize the exotic species common to numerous cities that was identified in activity #1 to evaluate how local context alters management prioritization. Further, cultural valuation and human perceptions will be used to determine if management actions are feasible. The workshop will evaluate the utility of the framework and alter it according to local valuation and to extend it to different management scenarios -like the use of biocontrol. The group will also design practitioner training workshops that show how to implement management frameworks and that can be translated and implemented elsewhere. A sub-group will explore the use of biocontrol in cities (led by S. Smith), which will engage with global and national biocontrol organizations.
4) Facilitate global communication: GUBIC will prioritize sustainability so that this platform to study and understand urban impacts on biodiversity and species invasion remains viable. We will create a distributed collaborative model that will oversee the instillation of standardized sampling design, and where new ideas, beyond what is articulated in this proposal, can be proposed and individual sites can participate in data collection or experiments. Essentially, one of the goals of GUBIC will be to create an inclusive global long-term collaboration. Further, each city represented in this network has explicitly made contact with non-academic partners that are responsible for natural area or species management in cities. The goal would be that policy and management frameworks that emerge will be translated for and workshops provided to these partnering organizations. GUBIC will apply to other foundations to create this mobilization structure.

Deliverables

GUBIC will achieve four major types of deliverable:

1) Scientific papers: This funding will produce at least 6 journal articles, which will appear in environmental and applied ecological journals. The papers will include: a synthetic overview on the need for alternative understanding and management of NIS in urban areas; three papers on global urban NIS patterns; two papers on the management framework and human perception and species by environment interaction.
2) Global urban invasion data set: GUBIC will compile various data to produce a global scale dataset of NIS patterns in cities around the world. This dataset will be made freely available on a searchable and sustainable data repository like Dryad.
3) Management training workshop: GUBIC will evaluate management decision-making frameworks and design training that can be translated for urban nature managers.
4) Courses: Some of the Toronto contributors will develop two courses: 1) an urban ecology senior undergraduate course, and 2) a graduate (in the Master's of Environmental Science program) course on urban management. In both of these, students will work alongside GUBIC to develop analyses and policy or management assessments.
5) Guiding GUBIC framework: The guiding documents for the formation of the global consortium and strategies for expansion funding will be pursued, specifically NSERC CREATE or NSERC Strategic Partnership grants. Along with this proposal, a IDRC will be created with Stellenbosch and then expanded to several other institutions.

Training

GUBIC will provide unparalleled training opportunities for graduate and undergraduate students. The postdoc and the four PhD students (two at UT and two at Stellenbosch) will have exposure to cutting edge to global societal and environmental issues and have truly unique opportunities to participate in a global collaboration. The two courses that go with this program will be globally unique courses, where student will work on projects that will have direct applied application. Further, a series a fourth-year undergraduate projects will be designed to supply workshops with preliminary data analyses, with a total of 6 such students participating. Further, the large symposium will be open to all faculty and students, and master's students in environmental science will have the opportunity to write papers based on symposium presentations.

Benefits to the University

This research thrust on the topic of NIS in urban areas is an inherently interdisciplinary area of scholarship and will draw on experts and training across diverse disciplines, from the social sciences to ecology. Enabling this collaborative activity would highlight recent academic priorities and initiatives that are differentiators for the University of Toronto and UT-Scarborough. Namely, both the University and the campus have identified urban studies as critical components for consolidation and investment. The new School of Cities initiative would immediate benefit from this proposal and an International Doctoral Cluster (with Stellenbosch) by giving a pathway for students to engage with faculty across the campuses, and for providing a nice bookend to urban initiatives across the campuses. Further, UTSC is investing in two initiatives of distinction around the environment and suburbanization, and workshops and other training experiences will engage with these emerging centres.

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The research consortium

Beyond the rich and diverse collaborative team at the University of Toronto, this funding will support a globally unique collaborative model that will raise the profile of the University. The collaborators making up the consortium have all signified their willingness to participate in GUBIC. We have research groups from 30 different cities, in 19 different countries represented in this network (see image below). This is a unique collaborative structure, where for each city we have a primary academic contact and a non-academic partner. We've clustered cities into regional hubs and for each hub, we have a single person acting as a member of the network coordination team, also referred to as the steering committee. The steering committee consists of: Marc Cadotte (University of Toronto); Myla Aronson (Rutgers University); David Richardson (University of Stellenbosch); Ingolf Kühn (Martin-Luther University Halle-Wittenberg); Petr Pysek (Institute of Botany, Academy of Sciences of the Czech Republic); Rafael Zenni (Universidade Federal de Lavras); and Inderjit Singh (Delhi University). The overall consortium is comprised of about 40 collaborators, including 18 women, and people at all career stages, from postdocs to Full Professors, and representatives from all continents. The collaborators include ecologists, urban scientists, modelers, sociologists, soil biologists, foresters, and political scientists. Five of the collaborators (Daniel Simberloff, David Richardson, Marc Cadotte, Petr Pysek, Wilfried Thuiller) are listed in Web of Science's top 1% of cited scientists in environmental science. Given the importance of one partnering institution, we have also submitted an application for an International Doctoral Cluster with Stellenbosch University.

The value of collaborative network is that individuals contribute unique perspectives informed by the specific locations in which they study and live and by the disciplines they are trained in, but also, they bring with them different datasets and local management frameworks and connections with municipal management agencies and NGOs.