

RESEARCH ARTICLE

Prioritizing terrestrial invasive alien plant species for management in urban ecosystems

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Award**Handling Editor:** Cate Macinnis-Ng**Abstract**

1. Invasive alien plant species (IAPs) in urban areas can have detrimental effects on biodiversity, ecosystem services and human well-being. Urban areas are complex social management mosaics with high land-use diversity, complex land tenure patterns and many different stakeholder groups, some of which derive benefits from invading species. Urban conservation practitioners face complex decisions about which IAPs require management. Yet most IAPs prioritization frameworks have been designed for and implemented in natural or rural areas and are generally inadequate for guiding effective and sustainable interventions in urbanized areas.
2. We modified an existing prioritization scheme to develop a framework for prioritizing terrestrial IAPs in urban areas which applies evidence-based (data-driven) and stakeholder-based (local knowledge) assessments to score and rank alien plant species in terms of their priority for management using an objective set of criteria.
3. The framework consists of 46 criteria, grouped into eight modules which assess invasion status, habitat requirements, biological characteristics, dispersal ability, distribution, impacts (positive and negative) and potential for control for each alien plant species under consideration.
4. We use the city of Toronto, Canada as a case study to test our framework—a list of 50 IAPs were effectively scored and ranked in order of high to low priority for control. Species with the highest *total prioritization scores* were *Vincetoxicum rosicum* (Dog Strangling Vine), *Convolvulus arvensis* (Field Bindweed) and *Taraxacum officinale* (Common Dandelion, ranked 1, 2 and 3 respectively).
5. Many of the identified high priority species align with those previously flagged as of management concern by conservation practitioners, but also include those that are not actively managed due to their perceived lower ecological impacts. These species still require high resource investment for other objectives such as aesthetics. This highlights the complexity of alien plant species management in urban areas.
6. *Synthesis and applications.* Prioritizing invasive alien plants for management in urban areas is particularly challenging due to often conflicting ecological, economic and social objectives. We use available evidence and local stakeholder knowledge to develop an objective and systematic prioritization tool which can

assist conservation practitioners in selecting priority species for management action in complex urban landscapes.

KEYWORDS

ecosystem services, impact, invasive alien plant species, management, prioritization, stakeholder knowledge, urban

1 | INTRODUCTION

Urbanization is expanding rapidly across the globe, placing pressure on natural ecosystems to provide services to burgeoning human populations (Elmqvist et al., 2013). Humans have intentionally imported alien species into towns and cities to satisfy this growing demand for ecosystem services (Gaertner et al., 2017; Potgieter et al., 2017). However, human activities associated with urbanization have also altered environmental conditions in cities which enables some alien species to establish and spread, thereby becoming invasive (Cadotte et al., 2017; Kowarik et al., 2011; Potgieter & Cadotte, 2020).

We define invasive alien plant species (IAPs) as 'introduced [plant] species with individuals dispersing, surviving and reproducing at multiple sites across a greater or lesser spectrum of habitats and extent of occurrence' (Blackburn et al., 2011). Some of these IAPs have adverse ecological, economic and social impacts. Yet, many urban residents still derive direct and indirect benefits from them such as local climate regulation, food provision, recreational opportunities and aesthetic appeal (Arrington, 2021; Dickie et al., 2014; Potgieter et al., 2017). Indeed, some IAPs can provide certain ecosystem services that otherwise might not have been present prior to their introduction (e.g. alien tree species introduced into historically treeless ecosystems for shade or firewood; Rundel et al., 2014). Furthermore, urban residents might have a fondness or familiarity with IAPs that can increase planting (and spread) and lead to opposition to control programs (Novoa et al., 2017).

Invasive alien plant species that are both beneficial and detrimental are likely to generate conflicts around their use and management (Dickie et al., 2014; Zengeya et al., 2017). Such conflicts often arise due to differences in value systems and to a lesser extent stakeholder and decision-maker's risk perceptions (Estévez et al., 2015; Shackleton et al., 2019). These differences can be pronounced in complex social landscapes such as towns or cities which typically have a greater number and diversity of stakeholders compared to rural and natural areas (Epanchin-Niell et al., 2010; Gaertner et al., 2016; Potgieter et al., 2019). This complicates management efforts as conservation practitioners need to balance the needs of different stakeholders while also meeting their mandate of protecting biodiversity, ecosystem services and human well-being (Krueger et al., 2012). To alleviate potential conflicts of interest that might affect attempts to control IAPs, the decision-making process should be transparent and consider opinions, perspectives and values of a wide range of stakeholders involved in urban land-use and ecosystem management decisions (Potgieter et al., 2018).

Limited resources means that not all IAPs can be managed. There is increasing pressure on practitioners to apply defensible, objective and transparent protocols for deciding which IAPs require priority control. Decisions to manage IAPs are often aimed at reducing negative impacts on ecosystems and society. However, while many frameworks are available to guide the quantification of positive and/or negative effects of IAPs (e.g. EICAT by Blackburn et al., 2014; Vaz et al., 2017; SEICAT by Bacher et al., 2018; Milanović et al., 2020), uncertainties in measuring and predicting these impacts persist, limiting our ability to effectively prioritize and manage invasions (Probert et al., 2020). As a result, impacts are too often assumed rather than quantified, and expenditure of valuable resources might be directed towards species that have relatively little or no impact (Hejda & Pyšek, 2006; Meffin et al., 2010). Therefore, decisions to manage IAPs in urban areas are often made on an ad hoc basis driven by needs, opinions and opportunities. These decisions are often prompted by external factors (such as funding availability, management directives or public opinion) that are not necessarily recorded in the formal literature (Potgieter et al., 2021). This limits the ability for practitioners to consider objective and transparent criteria. Innovative and adaptive, and importantly, repeatable approaches are therefore needed to enable strategic yet flexible IAPs management in urban landscapes. Although data-driven, scientific, evidence-based management is highly desirable, it is often challenging to gather robust and comprehensive data that are germane to local environmental and governance conditions within cities. However, evidence-based prioritization of IAPs for management is still possible where data are scarce. Even without baseline data on priority IAPs, the combined use of best available data along with local stakeholder knowledge can bolster prioritization approaches (McGeoch et al., 2016).

Prioritization using multi-criteria decision analyses has been widely used, especially for IAPs (Benke et al., 2011; Liu et al., 2011). Question- and score-based approaches, and other structured decision-making models allow for repeatable and transparent prioritization when the available information is inadequate (McGeoch et al., 2016). Various frameworks have been developed and implemented around the world for prioritizing invasive species (Brunel et al., 2010; Kumschick et al., 2012; Robertson et al., 2003), invaded areas (Forsyth et al., 2012; Mostert et al., 2019; Roura-Pascual et al., 2009), and pathways for the introduction and movement of alien species (Essl et al., 2015; Hulme et al., 2008; Scalera et al., 2016). Yet most IAPs prioritization frameworks are generally inadequate for guiding effective and sustainable interventions in urbanized areas

as they mostly assess negative impacts of alien taxa and have been designed for and implemented in natural or rural areas at larger spatial scales. Moreover, given the frequency with which new prioritization schemes are being developed and published, there is a greater need to test the applicability of previously developed schemes to different taxonomic groups and ecosystems (and at different spatial scales). To this end, we modified an existing prioritization scheme to develop a framework for prioritizing terrestrial IAPs for control based on their invasion status, habitat requirements, biological characteristics, dispersal ability, distribution, impacts (positive and negative) and potential for control using both evidence- and stakeholder-based assessments. The framework is designed for use in urban and near-urban systems, and we apply the framework in the most populous metropolitan area in Canada.

2 | MATERIALS AND METHODS

2.1 | Study area

The Toronto region (2,485 km² area) is the most populous metropolitan area in Canada and is one of the fastest growing urban areas in North America. It includes Metropolitan Toronto and four other regional municipalities (Durham, Halton, Peel and York). Its western, northern and eastern boundaries are defined by the limits of the nine watersheds for which the Toronto and Region Conservation Authority (hereafter, TRCA) has jurisdiction. The Toronto region is highly urbanized with a population over 6 million people and is forecast to be home to 10.35 million people by 2051 (Hemson Consulting Ltd, 2020). The per cent land cover is currently about 51% urban, 24% rural (including agricultural land uses) and less than 24% remaining natural cover (Toronto and Region Conservation Authority (TRCA), 2007). The terrestrial natural cover is primarily deciduous, mixed and successional forest (15.9%); small tracts of meadow (6.1%); wetland (1.6%); and Great Lakes shoreline habitats (0.1%; Toronto and Region Conservation Authority (TRCA), 2007). Despite the increase in awareness of conservation issues in the TRCA jurisdiction, there continue to be incremental losses of habitat while the quality of remaining habitat continues to decline.

This region is home to around 1,100 native plant species and an additional 830 alien plant species (Cadotte, 2021). There are more than 200 flora and fauna 'species of concern' that are at risk in the region due to habitat loss or sensitivity to urbanization.

Ethical clearance was granted by the Social Sciences, Humanities & Education Research Ethics Board, University of Toronto (protocol number 39563, approval date 18 August 2020).

2.2 | Framework design

Our species prioritization framework was based on the scheme developed by Robertson et al. (2003). Their framework is specifically designed for IAPs, can accommodate positive impacts of invasive

taxa (a crucial consideration in urban biological invasions assessments; Potgieter & Cadotte, 2020), can be applied at various spatial scales and can be customized according to the needs of the user by altering the modules and their weightings or modifying the criteria used for assessment. This scheme can also be used to assess a species' state of knowledge by applying a confidence score (detailed below). These features are particularly desirable for prioritizing IAPs management in complex social landscapes such as towns and cities.

The framework consists of a set of criteria, grouped into modules (Table 1). *Total prioritization scores*, calculated from *criterion* and *module scores*, were used to assess a species' priority. To account for uncertainty and availability of data for each criterion used in the assessment process, a separate index known as a *confidence score* was included. The lower the *confidence score*, the greater the uncertainty and amount of missing data for that criterion. This approach explicitly indicates a level of confidence in the *total prioritization score* assigned to a species. The *confidence score* can also be used as a measure of the state of knowledge of a given species (Robertson et al., 2003). The final ranking is calculated by multiplying both separate indices—the *total prioritization score* and the *total confidence score*. This approach integrates the plant species' priority with an index of data reliability.

As the criteria in Robertson et al. (2003) were developed for natural or rural areas in South Africa, we modified the criteria and modules to be applicable to urban areas and the Toronto region specifically. To do this, we drew from various sources including the Australian Weed Risk Assessment, the Millennium Ecosystem Assessment categorization of ecosystem services (Millennium Ecosystem Assessment, 2005) and several other primary studies (Potgieter et al., 2017; Vaz et al., 2017). These sources were selected based on the comprehensiveness of their assessment criteria and their relevance to the urban context. Relevant criteria from these sources were either directly included or modified and incorporated into our initial criteria list (i.e. before engaging with stakeholders). The overall format and scoring system of Robertson et al. (2003) were retained (see Appendix S1).

The prioritization framework consists of 46 criteria, grouped into eight modules that assess invasion status, habitat requirements, biological characteristics, dispersal ability, distribution, impact (positive and negative) and potential for control for each alien plant species under consideration (Appendix S1). Each of these modules includes at least one criterion (Table 1). Stakeholders from the TRCA were engaged in the initial development of the framework (e.g. criteria selection) and at intervals throughout the process to ensure the relevance of the framework for them as end users (Figure 1).

The framework is designed so that the user can customize the system by weighting the modules, but the criteria within those modules have fixed weightings (the highest weightings associated with the most undesirable characteristics) that cannot be altered by the user. While the framework also allows for modules to be weighted according to the requirements of the user, we did not attempt to obtain relative weightings for each module in our exercise here, rather we focused on the clarity and comprehensiveness of the criteria.

TABLE 1 The core elements of the prioritization framework showing the modules and criteria, and each criterion's weighting range. Highest weightings are associated with the most undesirable characteristics. See Appendix S1 for the comprehensive framework including all subcriteria

Modules	Criteria	Criterion weighting
Module A: Invasion status	• Invasive elsewhere	1–0
	• Closely related to invasive taxon	1–0
Module B: Habitat requirements	• Germination requirements	0–3
	• Seedling/propagule establishment requirements	0–3
	• Disturbance required for seedling establishment to occur	0–3
Module C: Biological characteristics	• Allelopathic properties	0–3
	• Normal growth rate	0–3
	• Stress tolerance of established plants to frost, drought, water logging, salinity, fire	0–3
	• Reproductive system	0–3
	• Number of propagules produced per flowering event	0–3
	• Propagule longevity	0–3
	• Frequency of sexual reproduction for mature plant	0–3
	• Time to reach reproductive maturity	0–3
Module D: Dispersal ability	• Number of dispersal mechanisms	0–3
	• Probability that propagules will disperse to a distance greater than 1 km	0–3
Module E: Distribution	• Distribution (relative abundance across the landscape)	0–3
Module F: Negative impacts	• Biodiversity	0–3
	• Health	0–3
	• Infrastructural damage	0–2
	• Leisure and recreation	0–2
	• Cultural and aesthetic	0–2
	• Security and safety	0–2
	• Potential control costs	0–2
Module G: Positive impacts	• Positive economic impact	0–4
	Provisioning services	0–3
	• Food/fibre	0–3
	• Fuel	0–3
	• Biochemicals, natural medicines and pharmaceuticals	0–3
	Cultural services	0–3
	• Recreation, and mental and physical health	0–3
	• Tourism	0–3
	• Aesthetic appreciation and inspiration for culture, art and design	0–3
	• Spiritual experience and sense of place	0–3
	Regulating services	0–3
	• Local climate and air quality	0–2
	• Carbon sequestration and storage	0–3
	• Water regulation	0–3
	• Erosion control	0–3
	• Pollination	0–3
	• Storm protection	0–3
	• Water purification and waste treatment	0–3
	Supporting services	0–3
	• Primary production	0–2
	• Provision of habitat	0–2
	• Soil formation and retention	0–2
	• Nutrient cycling	0–2
Module H: Potential for control	• Chemical control	3–0
	• Biological control	0–3
	• Mechanical control	3–0
	• Legislation	1–0

Constructing an unbiased and reliable set of module weights would require sampling many different stakeholder groups and requires further research. However, for our purposes here, stakeholders were

asked in an online survey (described below) to rank the modules in order of most to least important in prioritizing IAPs for management. An average ranking for each module was then calculated based on



FIGURE 1 Schematic overview of the invasive alien species prioritization process

the stakeholder's responses. Numerical weights corresponding to the ranks were derived using rank sum: $n - r_j + 1$ (n = total number of criteria; r_j = straight rank) and then normalized by dividing the individual weights by the sum of all weights. We applied these module weightings to the *module scores*—for each species, the weighted *module scores* were summed to calculate a final (weight-adjusted) *prioritization score*. These species were then ranked by this index.

2.2.1 | Developing a candidate species list

We used Cadotte's (2021) list of vascular plants for the city of Toronto as the source of alien plant species in the Toronto region. This list was compiled from several different species lists and cross-referenced for taxonomic verification. Six different plant lists that are actively updated were used, these included: a list compiled through the Cadotte laboratory research within and around the city of Toronto (e.g. Arnillas & Cadotte, 2019; Livingstone et al., 2020); a

list of the vascular plants for the Rouge National Urban Park; a master plant list from the Royal Ontario Museum (ROM, Royal Ontario Museum, 2018); plant observations for the Toronto region from the Global Biodiversity Information Facility (GBIF, Global Biodiversity Information Facility, 2020); a biological inventory of vascular plants provided by the TRCA from their ravine and woodlot monitoring; and a collation of natural history observations provided by a Toronto resident. See Cadotte (2021) for further details on the methodology used.

In the absence of empirical data on species abundance, estimates of abundance were included based on the number of occurrences in the GBIF and ROM lists, and the number of recorded species' observations in the TRCA biological inventories. A composite abundance measure was created from these estimates by scaling all three sets to between 1 and 100 and taking the average of the three. Either the scaled GBIF, ROM and/or TRCA estimates were used if the others were missing. A preliminary candidate species list was then created with the most recorded species (ranked in order of estimated

abundance). This list was limited to 50 candidate species due to time constraints of individual assessors. This preliminary list was presented and discussed at a stakeholder workshop where participants were given the opportunity to provide additional alien plant species considered priorities for management. The workshop participants recommended an additional 15 species to be added to the candidate species list—these 15 species replaced the bottom 15 species (ranked in order of estimated abundance).

2.2.2 | Prioritizing candidate species

Two approaches were used to prioritize candidate species: evidence- and stakeholder-based assessments (Figure 1). The framework was applied to each candidate species using evidence from the literature and from independent assessments provided by stakeholders.

2.2.3 | Evidence-based assessment

For each candidate species, a literature search was conducted using ISI Web of Science database and Google Scholar. We also searched the grey literature (such as fact sheets, management plans, online invasive species databases and theses). Species names (scientific and common) and generic synonyms were used as the search string for finding relevant information on each species. In addition to the species name, the following keywords were used in the search: *invasi** OR *nonnative* OR *non-native* OR *alien* OR *exotic* OR *weed*. Reference lists from all retrieved articles were screened to identify other relevant publications. Detailed searches were done on all retrieved articles to find information relevant to all criteria for each module. For example, for the 'habitat requirements' module, keywords searched for included: *disturb**, *establish**, *germinat**, and *seedling**. Only articles published in English from 1900 to 30 June 2020 were included in the search.

Evidence-based assessments were performed independently by the lead author on this paper for each candidate species. This author's informed opinion was used when published information was not available for a particular criterion (e.g. seedbank longevity), and the lowest *confidence score* was assigned. Scores were assigned to each criterion based on evidence obtained from the literature. The score for each criterion was divided by the maximum possible score (i.e. highest fixed criterion weighting) for that criterion to give the *criteria score* (Appendix S1). Scoring for each criterion was either binary or ordinal. The *module score* was calculated by dividing the sum of the *criteria scores* by the number of criteria in the module. The *total prioritization score* was calculated by totalling the *module scores*.

Confidence scores are assigned to each criterion based on the uncertainty and availability of evidence in the literature. If there was sufficient published evidence and data were certain (i.e. evidence was corroborated by at least two published literature sources and at least one of these sources presented quantitative or qualitative data), a *confidence score* of 1 was assigned; if data were uncertain

or based on unpublished data (i.e. grey literature) or experience, the *confidence score* was 0.5; and if data were missing or based on extrapolative interpretation of studies, the *confidence score* assigned was 0. A *module confidence score* was calculated for each module by summing the *criteria confidence scores* and dividing the number of criteria in that module. The *total confidence score* was calculated by taking the sum of the *module confidence scores*. The species were then ranked according to the *final prioritization score* which is calculated by multiplying the *total prioritization score* and the *total confidence score*.

2.2.4 | Stakeholder-based assessment

To initiate the stakeholder-based assessment of candidate species, a virtual stakeholder workshop was held on 28 July 2020. Ethical clearance was granted by the Social Sciences, Humanities & Education Research Ethics Board, University of Toronto (protocol number 39563, approval date 18 August 2020).

The workshop was attended by 19 stakeholders, who were selected based on their involvement in the management of IAPs in the Toronto region. They were drawn from several key groups including government staff (provincial and municipal), conservation authorities, stewardship councils and non-government and community organizations. The objectives of the workshop were to provide an overview of the approach used to develop the prioritization framework for IAPs management in the Toronto region; provide a detailed breakdown of the framework (including the modules, criteria and scoring system); and to gain feedback and input on the framework incorporating the diverse stakeholder views and priorities. To allow for stakeholders to provide assessments for each candidate species, the prioritization framework was transformed into an online survey using Google Forms. Once a detailed description of the framework and survey was provided, stakeholders were placed into breakout groups with each group assigned an example species from the candidate list to assess as a 'test run' using the survey. This ensured that the stakeholders were familiar with the framework and the structure of the survey. Feedback provided by the stakeholders during the workshop allowed the framework to be refined prior to the official assessment being conducted.

Following the workshop, the online survey was officially sent out to the workshop participants to be completed in their own time and/or by an associated technical delegate with more specialized knowledge on IAPs and their management. Due to time constraints, only the 30 highest-ranked species were allocated to stakeholders for assessment. The task of completing the survey was shared between stakeholders, with each candidate species being assessed by two stakeholders, that is two stakeholder assessments per species. In the cases where two assessments were provided for a species, an average *total prioritization* and *confidence score* was calculated. The survey responses were used to create a ranked priority species list based on the stakeholder's input. In the online survey, stakeholders were also asked to name any additional priority species that should

be considered for assessment, emerging alien plant species that should be added to a 'watch list'. These species can be assessed at any time using the framework to determine their relative priority ranking.

Candidate species were ranked according to the product of their *total prioritization score* and the *total confidence score* for both evidence- and stakeholder-based assessments (where applicable) and compared. These values were then combined and averaged to determine overall priority species rankings.

3 | RESULTS

In the evidence-based assessment, 50 species were ranked according to the product of their *total prioritization scores* and *total confidence scores* (Table 2). The highest-ranked species were *Vincetoxicum rossicum* (dog-strangling vine), *Convolvulus arvensis* (field bindweed) and *Taraxacum officinale* (common dandelion), ranked 1, 2 and 3 respectively. *Vincetoxicum rossicum* received the highest *total prioritization score* by a significant margin and the eighth highest *total confidence score* (Table 2). This resulted in a *final prioritization score* of 10 points higher than the second-ranked species. It also received the highest *final prioritization score* in the stakeholder-based assessment again scoring 10 points higher than the second-ranked species. The lowest ranked species were *Aegopodium podagraria* (goutweed), *Chelidonium majus* (celandine) and *Leonurus cardiaca* (common motherwort; ranked 48, 49 and 50 respectively).

To date, the online survey elicited 25 responses from stakeholders with only 20 species effectively assessed. Consequently, combined priority rankings from both evidence- and stakeholder-based assessments could not be established for all 50 species; however, comparisons were made for those 20 species assessed (Appendix S2). *Final prioritization scores* in the stakeholder-based assessment were on average 12.50 points lower for each species compared to the evidence-based assessments—only *Trifolium repens* received higher stakeholder-based scores. *Total prioritization scores* in the stakeholder-based assessment were on average 0.33 points lower for each species compared to the evidence-based assessments—only *Phragmites australis*, *Torilis japonica* and *Trifolium repens* received higher stakeholder-based scores. Similarly, *confidence scores* in the stakeholder-based assessment were on average 1.71 points lower for each species compared to the evidence-based assessments—only *T. officinale* and *Trifolium repens* received higher stakeholder-based scores.

Stakeholders ranked negative impacts, dispersal ability and potential for control as the most important modules, followed by biological characteristics and habitat requirements (Appendix S3). Distribution, invasion status and positive impacts were considered the least important modules. The normalized module weightings were applied to the *module scores* and used to calculate *final* (weight-adjusted) *prioritization scores* for each species (Appendix S4). The weight-adjusted scores revealed several positional changes in the species ranking. While *V. rossicum* remained the top-ranked species,

T. officinale moved up one position (rank 2) replacing *C. arvensis* (rank 3). While *Leonurus cardiaca* remained the bottom-ranked species, *Verbascum thapsus* (common mullein) and *Cirsium vulgare* (bull thistle) replaced *A. podagraria* and *Chelidonium majus* as the 48 and 49 ranked species. *Celastrus orbiculatus* moved up four positions to rank 5 and *Phragmites australis* moved up five positions to rank 7 (Appendix S4). The module weightings can be adjusted according to the requirements of the user—this can be done ad hoc or through more formalized methods such as the Analytical Hierarchy Process.

Stakeholders also identified 21 additional priority species, and nine emerging alien plant species for consideration (Appendix S5). These species should be assessed using the framework to determine their relative priority ranking. Stakeholders also identified 11 native species that should be considered as potential 'replacement' species (i.e. species that can be planted in the place of the removed IAPs) as they can provide similar ecosystem services with relatively minimal negative impacts (Appendix S5).

4 | DISCUSSION

The framework presented here uses available data and local stakeholder knowledge to inform the prioritization of terrestrial IAPs. The overall approach we developed established a set of clear, transparent and agreed priorities which can be used to help guide the allocation of available funds for controlling IAPs in complex management mosaics.

By applying the framework across the city of Toronto, Canada, a priority species list was developed in which IAPs were ranked according to their priority for management. *Vincetoxicum rossicum* received the highest *total prioritization score* by a significant margin and the eighth highest *confidence score* (Table 2). It also received the highest *final prioritization score* in the stakeholder-based assessment. This is likely due to increased research effort over the past 10 years to understand the species' impact and invasion dynamics in southern Ontario. As one of the most widespread invaders in the Toronto region, conservation practitioners have likely dedicated substantial resources to controlling this species over time. *Vincetoxicum rossicum* is a perennial herbaceous vine native to Ukraine (Kricsfalussy & Miller, 2008). It grows in a wide range of habitats and spreads quickly along roadsides, ditches and fence lines (DiTommaso et al., 2005; Douglass et al., 2009). Its seeds are spread long distances by wind and moving machinery or equipment with seeds attached. Seeds can also spread by falling into moving water and floating downstream (Ladd & Cappuccino, 2005). *Vincetoxicum rossicum* negatively impacts native biodiversity—it reduces plant diversity and other trophic levels by excluding species with certain traits (DiTommaso et al., 2005; Ernst & Cappuccino, 2005; Livingstone et al., 2020; Sodhi et al., 2019). It also produces allelopathic chemicals which can inhibit the growth of other plants and alter soil biota (Douglass et al., 2009).

Convolvulus arvensis received the second highest *total prioritization score*. It is a climbing herbaceous perennial native to Eurasia (Austin, 2000). It occurs throughout Ontario in cultivated fields,

TABLE 2 List of 50 invasive alien plant species ranked according to the product of their total prioritization score and the total confidence score, using evidence-based assessments with equal weights assigned to all modules

Rank	Species	Common name	Total prioritization score (max = 8)	Total confidence score (max = 8)	Final prioritization score (max = 64)
1	<i>Vincetoxicum rossicum</i>	Dog-strangling vine	6,51	7,44	48,48
2	<i>Convolvulus arvensis</i>	Field bindweed	6,06	7,30	44,21
3	<i>Taraxacum officinale</i>	Common dandelion	6,15	7,18	44,16
4	<i>Lonicera tatarica</i>	Tatarian honeysuckle	5,85	7,42	43,47
5	<i>Solanum dulcamara</i>	Bittersweet nightshade	5,96	7,22	43,03
6	<i>Ligustrum vulgare</i>	European privet	5,89	7,24	42,68
7	<i>Rhamnus cathartica</i>	Common buckthorn	6,03	6,97	42,01
8	<i>Echium vulgare</i>	Common viper's bugloss	5,39	7,60	40,98
9	<i>Celastrus orbiculatus</i>	Oriental bittersweet	5,70	7,18	40,96
10	<i>Rosa multiflora</i>	Multiflora rose	5,86	6,96	40,74
11	<i>Impatiens glandulifera</i>	Himalayan balsam	5,33	7,46	39,75
12	<i>Phragmites australis</i>	Phragmites	5,37	7,39	39,66
13	<i>Cirsium arvense</i>	Creeping thistle	5,99	6,55	39,24
14	<i>Vinca minor</i>	Periwinkle	5,32	7,34	39,06
15	<i>Elaeagnus angustifolia</i>	Russian olive	5,32	7,27	38,67
16	<i>Reynoutria japonica</i>	Japanese knotweed	5,73	6,74	38,65
17	<i>Acer platanoides</i>	Norway maple	5,63	6,76	38,07
18	<i>Elaeagnus umbellata</i>	Autumn olive	5,44	6,99	38,02
19	<i>Barbarea vulgaris</i>	Bitter wintercress	5,04	7,50	37,80
20	<i>Rumex crispus</i>	Curly dock	5,58	6,75	37,66
21	<i>Alliaria petiolata</i>	Garlic mustard	5,54	6,79	37,61
22	<i>Potentilla recta</i>	Sulphur cinquefoil	5,61	6,67	37,44
23	<i>Phleum pratense</i>	Common timothy	4,91	7,61	37,36
24	<i>Crataegus monogyna</i>	Common hawthorn	5,08	7,32	37,24
25	<i>Hypericum perforatum</i>	Common St. John's-wort	5,09	7,31	37,18
26	<i>Plantago major</i>	Common plantain	5,53	6,71	37,06
27	<i>Tussilago farfara</i>	Colt's-foot	5,15	7,11	36,60
28	<i>Torilis japonica</i>	Erect hedgeparsley	4,97	7,34	36,47
29	<i>Elymus repens</i>	Creeping wildrye	5,32	6,72	35,78
30	<i>Lythrum salicaria</i>	Purple loosestrife	5,43	6,56	35,59
31	<i>Vicia cracca</i>	Tufted vetch	5,35	6,61	35,38
32	<i>Dactylis glomerata</i>	Orchard grass	4,64	7,61	35,29
33	<i>Pastinaca sativa</i>	Wild parsnip	4,80	7,33	35,16
34	<i>Trifolium repens</i>	White clover	5,13	6,68	34,30
35	<i>Linaria vulgaris</i>	Butter-and-eggs	5,08	6,69	34,01
36	<i>Campanula rapunculoides</i>	Creeping bellflower	4,71	7,18	33,80
37	<i>Convallaria majalis</i>	European lily-of-the-valley	4,51	7,46	33,66
38	<i>Daucus carota</i>	Wild carrot	4,76	6,97	33,15
39	<i>Trifolium pratense</i>	Red clover	5,38	6,12	32,92
40	<i>Cichorium intybus</i>	Chicory	5,65	5,63	31,85
41	<i>Ranunculus acris</i>	Tall buttercup	4,81	6,54	31,46
42	<i>Verbascum thapsus</i>	Common mullein	4,54	6,91	31,35
43	<i>Robinia pseudoacacia</i>	Black locust	4,50	6,86	30,89

TABLE 2 (Continued)

Rank	Species	Common name	Total prioritization score (max = 8)	Total confidence score (max = 8)	Final prioritization score (max = 64)
44	<i>Hesperis matronalis</i>	Dame's rocket	4,38	6,98	30,61
45	<i>Epipactis helleborine</i>	Eastern helleborine	4,97	6,01	29,87
46	<i>Glechoma hederacea</i>	Ground ivy	4,20	7,07	29,69
47	<i>Cirsium vulgare</i>	Bull thistle	4,63	6,26	29,01
48	<i>Aegopodium podagraria</i>	Goutweed	4,21	6,69	28,15
49	<i>Chelidonium majus</i>	Celandine	4,58	5,96	27,29
50	<i>Leonurus cardiaca</i>	Common motherwort	4,56	4,78	21,82

gardens, lawns, roadsides and highly disturbed areas (Jacobs, 2007). This species grows rapidly and can out-compete native vegetation, and agricultural and horticultural crops for nutrients, moisture, light and space (Weaver & Riley, 1982). Due to its climbing ability, neighbouring plants can become smothered leading to a loss in biodiversity and a reduction in crop yield. Controlling this species is difficult due to the longevity of seeds in the soil bank (up to 20 years) and the ability of small fragments of rhizome to produce new shoots (Weaver & Riley, 1982). *Taraxacum officinale* received the third highest *total prioritization score*. It is a perennial herbaceous species that likely originated in Europe but is now found in most countries of the world (Holm et al., 1997). It can thrive under a broad range of climatic and soil conditions and has high reproductive and regenerative potential (Simon et al., 1996). Dispersal by wind, water, animal and bird vectors, and by various agricultural practices can result in the spread and successful establishment into new areas (Bostock & Benton, 1979).

Convolvulus arvensis and *T. officinale* received high *total prioritization* and *confidence scores* owing to the large body of literature describing their invasion success in many countries around the world. While the 'negative impacts' *module scores* for these species were relatively low (suggesting no significant realized negative impacts), the *module scores* for dispersal ability, distribution and habitat requirements were relatively high. While these species are ranked high on the priority species list for the Toronto region, they are seldom actively managed by conservation organizations such as TRCA as their perceived impact is considered low compared to other IAPs. However, this does not mean these species receive no management at all. As common weeds of residential gardens (e.g. lawns), homeowners frequently control these species at their own cost through manual removal and/or herbicide treatments usually as a means of improving the aesthetic of their gardens (Jacobs, 2007; Schnick & Boland, 2004). Therefore, the overall cost to control these species across the Toronto region is likely very high.

For the 20 species assessed by stakeholders, *total prioritization scores* and *confidence scores* were on average lower for each species compared to the evidence-based assessments (Appendix S2). The stakeholder assessments rely on the participant's knowledge on and experience with each species assessed. When faced with knowledge gaps and other forms of uncertainty, stakeholders are more likely to assign lower scores (Dahlstrom-Davidson et al., 2013). The lower

total confidence scores suggest a perceived lack of knowledge and experience associated with each species, which likely resulting in a lower criterion score being assigned.

Species which have both high *total prioritization scores* and high *total confidence scores* are most likely to pose serious problems. These are species in which the greatest number of resources (human and economic) should be invested. Compared to other IAPs that have potential to enact greater ecological harm, species with low *total prioritization scores* and high *total confidence scores* are currently of lower concern, for example *Dactylis glomerata* (orchard grass), *Convallaria majalis* (European lily-of-the-valley) and *Glechoma hederacea* (ground ivy; ranked 34, 39 and 48 respectively). Species with relatively high *total prioritization scores* but low *total confidence scores* (e.g. *Cichorium intybus* and *Cirsium arvense*) indicate an urgent need for further research to obtain more data which will improve confidence in their prioritization score and hence their rank. Emerging invaders are often overlooked because they have few realized negative impacts compared to widespread invaders. However, they have the potential to cause severe negative impacts in the future if not carefully monitored. It is critical to incorporate these species into alien plant monitoring programs. It is best to take a cautious approach—these species should be treated as serious until evidence, through careful monitoring and research, to the contrary is provided. Justifying large investment of resources in these species can be more difficult than in those with high *total prioritization* and high *total confidence scores*. Species with low *total prioritization scores* and low *total confidence scores* are of relatively higher concern and should be monitored. These species could be more problematic than their *total prioritization scores* suggest, but more data are needed to improve confidence in their priority ranking.

The list of priority species will only be valid for a limited period because the status of the species can change due to successful intervention strategies, changes in legislation, introduction of new species or increases in abundances of certain species. However, as new data become available and as levels of understanding of the dynamics of plant invasions improve, rankings and weights can be adjusted, and criteria can be added or removed. The framework design is flexible and allows the user to modify the criteria used for assessment and customize the system by weighting the modules. The output of the prioritization framework relies on sound ecological evidence and stakeholder input, yet robust data on many

aspects of IAPs are still lacking, particularly in urban areas. As new data become available, the scores assigned to each species can be adjusted accordingly and the priority rankings updated to reflect the new information.

While the framework presented here provides a comprehensive set of assessment criteria, the positive and negative impacts modules can exclude potentially important criteria (depending on the context in which the framework is applied). For example, 'leisure and recreation' is a criterion included in both the positive and negative impact modules; however, the 'tourism' criterion is only included in the positive impact module. While IAPs can have no positive effect on tourism, there are instances where they can negatively impact tourism. To address this, additional criteria would need to be included in the 'negative impacts' module. The framework is flexible and can accommodate such changes; however, this approach lengthens the framework and risks compromising its utility.

5 | CONCLUSIONS

The prioritization framework presented here serves as a useful decision support tool for conservation and research organizations, not only for Toronto, Canada but other complex management systems around the world and at various spatial scales. The framework can be tailored to meet the needs of these organizations by altering the module weightings or modifying some of the criteria used for assessment. The framework can also be used to assess different taxonomic groups, though more work is needed to determine which aspects require modification to effectively assess other taxa. The framework is also useful in assessing the state of knowledge of IAPs by applying a confidence score in the assessment process which serves as an indicator of available data and stakeholder knowledge.

It is important to improve the communication and collaboration among different stakeholders involved in IAPs management to foster strategic and coordinated approaches to IAPs management, minimize duplication of effort and use limited resources more effectively. This is especially true in urban landscapes where IAPs management strongly affects and is affected by various stakeholders and multiple objectives for ecosystem functioning and services. Strategic knowledge related to priority IAPs for management will enable stronger collaboration and coordination among these stakeholders where each can incorporate IAPs priorities into their own operational mandates and priorities.

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CONFLICT OF INTEREST

The authors do not have any conflict of interest to declare.

AUTHORS' CONTRIBUTIONS

All authors contributed to the conception and design of the study; L.J.P. performed the species assessments and conducted the analyses; L.J.P. led the writing of the manuscript; M.W.C. and N.S. provided funding and material support. All authors contributed critically to the draft and gave final approval for publication.

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DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository <https://doi.org/10.5061/dryad.h9w0vt4k3> (Potgieter et al., 2021).

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