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Prioritization and thresholds for managing biological invasions in urban ecosystems

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Abstract
Urban areas are hubs for invasive alien (non-native) species (IAS) which can cause major problems in and around urban areas. Urban conservation practitioners face complex decisions about which IAS require management, where and when these management interventions are necessary, and how to implement them effectively. While researchers increasingly advocate the assignment of critical thresholds informing IAS management decisions, little attention has been given to the development of criteria for such thresholds or related practical application protocols in the context of urban environmental management. We review approaches that have been applied to manage IAS in urban areas and evaluate which thresholds are considered and applied before, during, and after management actions. Our literature search revealed 75 publications, with clear geographic bias. Less than half of all studies had implications for the prioritization of IAS management in urban areas and only 31% of these directly assessed such priorities. Only 8% of studies referenced a threshold or decision trigger when proposing management approaches for IAS in urban areas. This suggests that decisions to manage IAS in urban areas are often made on an ad hoc basis, without considering objective and transparent criteria, and/or are prompted by external factors (such as funding availability) that are not recorded in the formal literature. There is a need for IAS management in urban areas to be evidence-based and informed by well-tested measures and transparent decision triggers. Resources should be directed towards integrating evidence-based thresholds and tailored prioritization schemes into urban management frameworks to support decisions about what, where, and when IAS management is required.

Keywords Decision trigger · Invasive alien species · Management · Prioritization · Threshold · Urban ecosystems

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Introduction

As hubs of human activity, urban areas experience a greater influx of alien species introductions (accidental and intentional) than rural or natural areas (Rebele 1994). As the world's human population becomes increasingly urbanized and globally connected, this influx will continue to increase (Perrings et al. 2010; Essl et al. 2011). Human activities (e.g., increased disturbance, resource supplementation, transport networks) provide many opportunities for alien species to establish, proliferate, and spread, thereby facilitating invasions within the urban matrix and into natural areas within and surrounding urban areas (Kowarik 2011; Cadotte et al. 2017; Potgieter and Cadotte 2020). These invasive alien species (IAS, defined here as "introduced 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), can have significant impacts on biodiversity, ecosystem functioning, ecosystem services, and human well-being (Pejchar and Mooney 2009; Gaertner et al. 2017).

Urban areas present a complex "management mosaic" (Epanchin-Niell et al. 2010) and exemplify a classic collective-action problem (Olson 1965), requiring cooperative and coordinated management across multiple organizations. As these management mosaics become more complex, management of IAS and their associated impacts becomes more difficult, and urban conservation practitioners are facing increasingly complex decisions about why, what, where, and when IAS management is required (Gaertner et al. 2017).

Why manage biological invasions in urban settings?

The stark differences in biotic and abiotic features of the urban environment compared to natural and rural ecosystems means that the impacts of biological invasions in urban areas manifest in different ways. For example, the Polyphagous Shothole Borer (*Euwallacea fornicatus*), an ambrosia beetle native to Southeast Asia, has been introduced into Israel, California, and South Africa where it, along with its fungal symbionts, causes significant and costly damage to urban forests (Paap et al. 2018; de Wit et al. 2021).

Socio-ecological and economic impacts resulting from invasions might be experienced more acutely in urban areas due to high human population densities. For example, the pollen of Common Ragweed (*Ambrosia artemisiifolia*) is highly allergenic and significantly impacts the health of residents in many urban areas across its invaded range in Europe (Smith et al. 2013). Invasive mosquitoes (e.g., Tiger Mosquito, *Aedes albopictus*) act as vectors of human and animal diseases, which are realized most acutely in areas with high human population densities (Eritja et al. 2005; Juliano and Lounibos 2005). Loss of trees from streets, yards, and parks resulting from the invasion of Emerald Ash Borer (*Agrilus planipennis*) in the eastern United States and Canada negatively affects human health (Donovan et al. 2013), property values (Li et al. 2019), and stormwater run-off (Gamboa 2009), while incurring substantial economic costs for the treatment and/or removal and replacement of high-value trees in urban areas (Herms and McCullough 2014). In South Africa, invasive alien trees such as Australian acacias (wattles), eucalypts, and pines increase the frequency and intensity of wildfires at the urban-wildland interface, negatively impacting on biodiversity and the safety of urban residents (van Wilgen et al. 2012). Moreover, the aquatic invader, Eurasian Milfoil (*Myriophyllum spicatum*), reduces lakefront property values along an urban–rural gradient in King County, Washington, USA (Olden and Tamayo 2014). However, such impacts are highly context-specific and are likely to vary substantially across different spatial and temporal scales. To mitigate the negative impacts of IAS, appropriate methods are required, including eradication, reduction below a specific threshold, or containment (Kumschick et al. 2012).

Invasive alien species can also provide benefits to urban residents (Potgieter et al. 2017). For example, most of the alien plants in Europe, such as the Empress Tree (*Paulownia tomentosa*) in Central Europe (Essl 2007), were deliberately introduced for horticultural and ornamental purposes (Lambdon et al. 2008; Pyšek et al. 2009; La Sorte et al. 2014) and provide various economic, environmental, and social benefits to people. However, over time, some of these species spread beyond sites of original containment or captivity to become invasive, and some negatively impact biodiversity, ecosystem services, and human well-being. As positive and negative impacts of IAS emerge over time, managing IAS to achieve desired outcomes becomes increasingly difficult. Managing species that are both detrimental (e.g., to biodiversity) and beneficial (e.g., providing shade) can result in conflicts among stakeholders (Dickie et al. 2014). This is particularly apparent in urban areas, which have a higher number and diversity of stakeholders whose priorities are informed by value judgements (Potgieter et al. 2019a).

What should be managed and where to manage it?

Invasive alien species can be very costly to manage and investing limited resources in their management comes at the expense of other priorities (Irlich et al. 2017; Cuthbert et al. 2021; Diagne et al. 2021). Therefore, resources must be directed to where they will be most cost-efficient (Krug et al. 2009). Conservation practitioners must prioritize their actions according to the magnitude of the actual and potential impacts of IAS on biodiversity and ecosystem functioning, ecosystem services, and human well-being (sensu ecosystem cascade model by Haines-Young and Potschin 2010). Resources available for management, the magnitude and nature of invasions, and relevant societal values vary significantly between countries but also between cities (and towns, or other jurisdictions) within a country (Pyšek et al. 2008; McGeoch et al. 2010).

Prioritizing management of IAS in urban settings is especially challenging due to often conflicting ecological, economic, and social objectives (Potgieter et al. 2018; Mostert et al. 2019). The heterogeneity of the landscape in terms of land use, tenure and ownership, mandates, and stakeholder perceptions of threats and priorities further complicates attempts to set management priorities. Consequently, the management context for prioritization can vary widely in scope and objective. Effective prioritization must consider not only IAS and associated vectors and pathways of spread, but also which sites are most sensitive (areas vulnerable to the impact of invasions) and susceptible (areas that are most exposed to invasion or where IAS are likely to establish and spread) to invasion (Fig. 1; McGeoch et al. 2016).

Furthermore, prioritization approaches should explicitly consider the magnitude of effects (positive and negative) on the environment, the economy, and society to minimize and reconcile potential conflicts when management actions are carried out (Kumschick et al. 2012).

Prioritizing IAS management in urban areas can take place within and across stages of the invasion process, both before (i.e., transport stage) and after the introduction of an alien taxon (Fig. 1), and management decisions can be approached in different ways. For example, pre-introduction risk assessments can be used to predict which alien species could be problematic if introduced into an area (Kumschick and Richardson 2013); decisions then relate to the implementation of policies to prevent or regulate species' introduction. Urban landscapes often act as the first point of entry for many alien species, and strategies that prevent the introduction of alien species often prove more cost-efficient than those that respond to incursions (species that have been introduced but have yet to spread or are in the early stages of invasion; Hulme 2006; Wilson et al. 2016; Padayachee et al. 2019). Each prioritization approach (species, pathways, sites) has particular data requirements, including evidence for known impacts (positive and negative), pathways of introduction, IAS abundance, vectors of spread, spatial data on vulnerable biodiversity, and ecosystem service values. However, such information generally has high levels of uncertainty, especially for urban areas, and is often based solely on expert judgements (Leung et al. 2012). While many IAS are

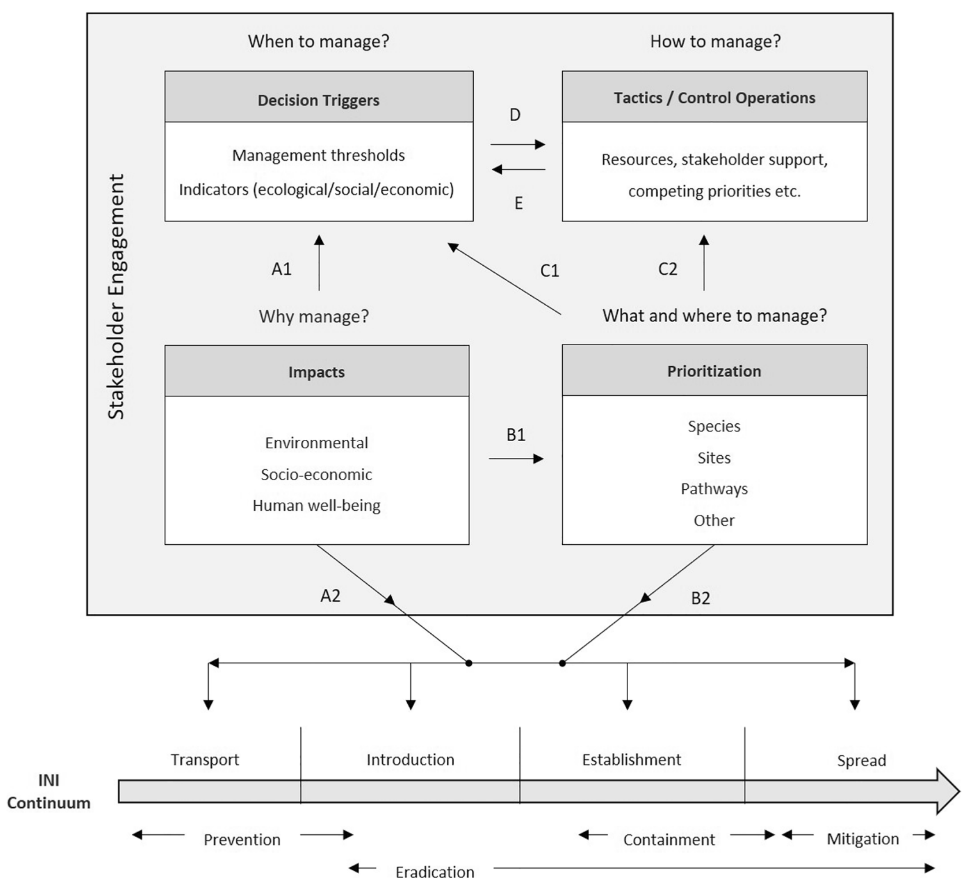

Fig. 1 A framework of key considerations for establishing invasive alien species (IAS) management thresholds to inform decision-making in urban areas and how they relate to the stages of invasion. Setting decision triggers requires an attribute to be identified (ecological, economic, and/or social) to serve as an indicator for the state of the system or the invasion process that is the target for management. A1 – An assessment of the impacts of IAS in urban areas can be used as a means of setting management thresholds. A2 – These impacts tend to increase along the introduction-naturalization-invasion continuum and can manifest in different ways, affecting various aspects of the socio-ecological system. B1 – Prioritization approaches can incorporate IAS impact assessments. B2 – Prioritization can occur at all stages of the INI continuum; for example, high-risk introduction pathways can be prioritized before any impacts are realized (risk assessments). C1 – Decision triggers can be developed once priorities have been established (informed by impact assessments), however (C2) additional barriers can impede tactical IAS control operations. D – Decisions to manage IAS in urban areas can be made on an ad hoc basis without following impact and prioritization assessments, or are prompted by external pressures, such as funding availability or political pressure. E – These barriers can influence the development and application of thresholds for managing IAS and subsequent decision triggers. Engaging with diverse stakeholder groups can better inform decisions about what, when, and where IAS management is required

similarly problematic in different countries and urban areas, the type and magnitude of IAS impacts can be highly variable and site-specific, making generalization difficult (Virtue et al. 2001). Effective communication and sharing of best management practices between urban areas can fill these knowledge gaps and accelerate action.

When to manage biological invasions in urban areas?

A management threshold is the value or range of values of an attribute that, once crossed, indicates when management intervention is required to address undesirable ecosystem changes (Fig. 2; Cook et al. 2016). For example, conservation practitioners in the Kruger National Park, South Africa, use a set of monitoring endpoints, known as thresholds of potential concern (TPCs), that together define the upper and lower limits along a continuum of change in selected environmental indicators (Foxcroft 2009).

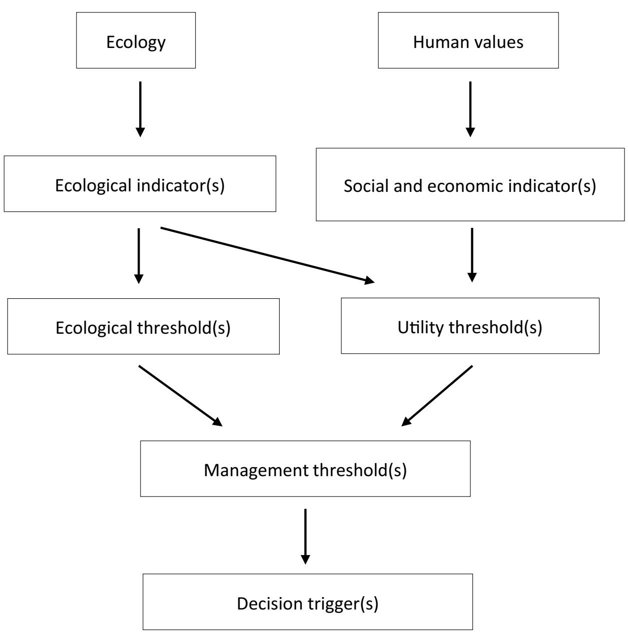

Fig. 2 The relationship between the different types of thresholds and decision triggers (modified from Martin et al. 2009). *Ecological thresholds* represent the value (point or range) that signifies rapid or irreversible change in an attribute, which reflects a change in the state of an environmental variable. *Utility thresholds* are determined subjectively and reflect stakeholder perspectives and values. *Management thresholds* represent the value (point or zone) of an attribute that once crossed characterizes when management intervention is required to address undesirable ecosystem changes. They are conditional on, and derived from, ecological and utility thresholds. *Decision triggers* represent the value of an attribute that once exceeded triggers a management action. Setting a decision trigger requires the identification of an ecological, social, or economic attribute that can serve as an indicator for the state of the system or the threatening process that is the target for management

Decision triggers represent the value of an attribute that once exceeded indicate the need for a management action (Fig. 2; Cook et al. 2016). Decision triggers offer urban conservation practitioners clarity and precision about when intervention in a system is justified (Bennetts et al. 2007; Guntenspergen 2014). They can be informed by human value judgements (utility thresholds) that integrate stakeholder priorities (e.g., maintaining a population of a flagship species at a level that will attract visitors to a protected area) and by ecological knowledge about the state of the ecosystem (ecological thresholds) (Fig. 2; Martin et al. 2009). Decision triggers can be set using several methods, depending on the number of management objectives and the availability of scientific data, expertise, and resources. Setting a decision trigger requires the identification of an ecological (e.g., species, ecosystem, or threat), social, or economic attribute that can serve as an indicator for the state of the system or the threatening process that is the target for management (Fig. 2; Cook et al. 2016).

There are subtle yet important differences between management thresholds and decision triggers. A decision trigger can be designed to occur at a threshold recognized by the management organization to require a specific response. Decision triggers and thresholds can be the same in many circumstances, but not all thresholds necessarily trigger management actions. Management thresholds can be used to capture both ecological and utility thresholds, either of which can trigger management action (Fig. 2). The key distinction between management and ecological thresholds is whether it is the ecosystem that undergoes change (ecological thresholds) or the management of that ecosystem (management thresholds) that undergoes change when a threshold is crossed (Bennetts et al. 2007). Decision triggers can be informed by existing ecological thresholds (Martin et al. 2009), assisting practitioners to prevent undesirable shifts in ecosystems (e.g., Carpenter et al. 1999). They can also be designed to manage more gradual and continuous ecosystem changes (Lookingbill et al. 2014) or *a priori* environmental targets (Moldan et al. 2012), whereby the desired ecosystem condition is defined, and triggers are set to maintain the system within a preferred ecological state (i.e., utility thresholds). Decision triggers can also be revised to change with policy, cultural perception, and shifting baselines of acceptable change.

Profound changes to the underlying biotic and abiotic components of ecosystems by urbanization blurs the 'natural' and baseline states of landscapes (Hobbs et al. 2006). The heterogeneity of the urban landscape suggests that management thresholds (and subsequent decision triggers) are likely to vary substantially across spatial and temporal scales within and among urban areas and perhaps even neighbourhoods. Conversely, urban areas might be similarly heterogeneous in composition and configuration (especially compared to areas outside the urban boundary), and so, once evaluated, management thresholds in one urban area might be similar to another. Some IAS are intricately woven into the urban fabric and their impacts can manifest in different ways. As a result, various ecological (e.g., species abundances), economic (e.g., damage costs), or social (e.g., public grievances) indicators can be assigned management thresholds that will trigger management action (Fig. 1).

Existing management threshold models mostly account for impacts on biodiversity (e.g., Panetta and Gooden 2017) or ecosystem structure, function, and composition (e.g., Foxcroft 2009), and are developed for natural and protected areas. However, the application of thresholds and decision triggers in the context of IAS management in urban settings remain largely unexplored. Here, we reviewed the scientific literature on IAS management approaches in urban areas and evaluated whether prioritization, management thresholds, and decision triggers are used to inform the management of biological invasions in urban areas.

Methods

Data collection

We reviewed the scientific literature, using ISI Web of Science, to identify commonly used prioritization approaches, decision triggers, and management thresholds for IAS in urban areas. The following keywords were used in our search: (urban* OR suburban OR city OR cities OR town OR metropol* OR built-up OR municip*) AND (manage* OR control OR eradicat* OR priorit* OR framework OR rank OR hierarch* OR threshold OR trigger) AND (invasi* OR nonnative OR non-native OR alien OR exotic OR pest OR weed) AND (impact* OR detection* OR risk* OR surveillance). This search string was applied to the titles, abstracts, and keywords in the Web of Science database (see Online Resource 1). Reference lists from all the retrieved articles were screened to identify other relevant publications.

We also searched the Applied Ecology Resources (AER, https://www.britishecologicalsociety.org/applied-ecology-resources/) database, an online, open-access collection of peer- and non-peer-reviewed information source. While this database is a recent innovation and currently lacks a critical mass of material, applying our search criteria to this database yielded no results.

We limited our database to relevant fields of study by using the "refine" function in Web of Science to exclude non-relevant subjects, such as medicine, engineering, or physics. The title and abstract were used to determine the relevance of the study. We only searched for English language publications and included records from 1900 to 5 February 2020. We did not attempt to redefine "invasive" and accepted the authors' categorization of species as invasive.

Analysis

Primary studies and review papers were included in our analysis. We broadly defined urban areas as ecosystems in which humans live at high densities and where built infrastructure covers a large proportion of the land surface (Pickett et al. 2001). As a result, urban areas were defined according to the study's designation. Studies that referenced aspects related to urbanization, but were conducted in natural or rural areas, were excluded. Only studies that directly assessed or reviewed IAS in the context of urban areas were included in the analysis, regardless of the scale at which the study took place. For example, studies that reviewed invasive taxa in urban areas across the globe were included in the analysis. If specific urban areas were not explicitly stated in a study, a more detailed search (e.g., checking data provided in a repository) was done to determine if the assessment took place in or near an urban area. Studies conducted on the outskirts of urban areas or within large tracts of relatively undisturbed, natural fragments in urban areas (e.g., urban forests) were included in our analysis.

For each study that met the inclusion criteria, the following information was recorded: (a) literature source; (b) spatial scale; (c) country; (d) taxon name; (e) taxonomic group; (f) framework development; (g) management recommendations; (h) prioritization implications; (i) priorities directly assessed; (j) taxon density or abundance; (k) species richness; (l) stakeholder approach; (m) species' impacts (positive and negative); (n) management threshold or decision trigger; and (o) relevant threshold or trigger metric. Online Resource 1 provides a description and the format in which the information was recorded.

Results

Our search captured 336 publications indexed in ISI Web of Sciences. After excluding non-relevant subjects, a total of 137 records remained. A final detailed screening yielded 75 publications which met all our inclusion criteria and were retained for the purposes of our review. Most studies excluded from our analysis either briefly referenced biological invasions in urban areas (i.e., this was not the focus of the study) or failed to discuss IAS specifically in the context of urban areas (e.g., invasions in rural areas).

Global patterns

Our analysis showed that Africa (excluding South Africa), Asia, and South America are understudied in the context of managing biological invasions in urban areas (Fig. 3a). Indeed, relative to the number of cities per area, much of Europe too remains largely understudied. At the

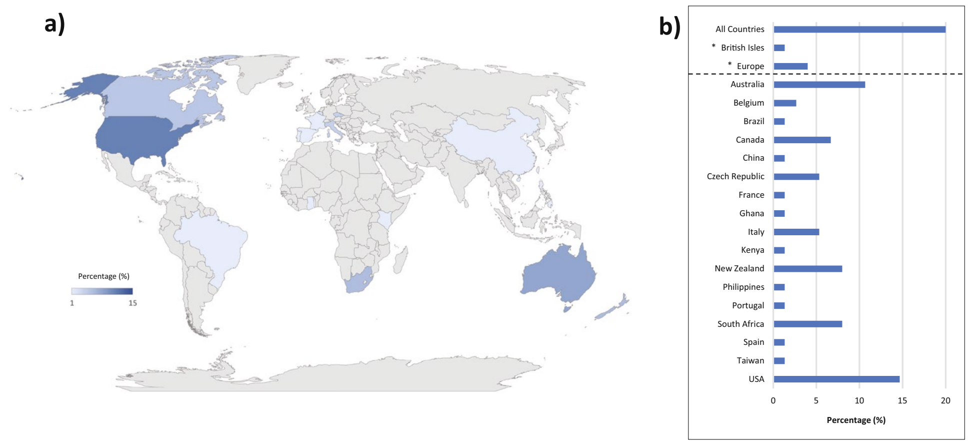

Fig. 3 Percentage of studies assessing invasive alien species prioritization approaches and thresholds for managing biological invasions in urban areas. **a**) Geographic distribution, and **b**) proportion of studies included in the analysis at the country scale (studies at smaller spatial scales were scaled up to country level). *Includes studies in which multiple countries were assessed. Several studies were conducted at the city scale, but for multiple cities across the world

country-scale, the highest proportion of studies was from the USA (15%), Australia (11%), New Zealand (8%), and South Africa (8%) (Fig. 3b). After scaling up all studies at the country scale, the highest percentage of studies that provide prioritization, thresholds, or decision triggers, and recommendations for management are at a global scale (20%) (Fig. 4a). At the country-scale – with the caveat that only peer-review literature in English journals were assessed – Australia, South Africa, the USA, and New Zealand are the only countries in which prioritization, thresholds, and recommendations for management have all been assessed (Fig. 4a).

Taxa

Eighty-five percent of studies assessed individual taxonomic groups, 4% assessed more than one taxonomic group, and 11% examined taxa across all major taxonomic groups in urban areas. Plants (45%) and insects (19%) were the best-represented taxonomic groups and together account for almost two-thirds of the taxa studied (Fig. 4b). Commonly studied alien plant species included *Pittosporum undulatum* (Australian Cheesewood), *Robinia pseudoacacia* (Black Locust), and *Vincetoxicum rossicum* (Dog Strangling Vine). Of those studies assessing a single taxonomic group, 56% assessed individual taxa and 22% assessed multiple taxa. Twenty-eight taxa were recorded across six taxonomic groups – the most studied species were *Aedes albopictus* (Asian Tiger Mosquito), *Agrilus planipennis* (Emerald Ash Borer), and *Felis catus* (Domestic Cat).

Why manage: impacts

Forty-nine percent (n = 37) of studies considered negative impacts of biological invasions in urban areas (on biodiversity and ecosystem functioning, and/or ecosystem services), while 24% (n = 18) included both the negative impacts and benefits of IAS. Only 27% (n = 10) incorporated stakeholder views into their impact assessments. All these studies assessed negative impacts while 70% assessed the benefits of IAS (Table 1). For example, Potgieter et al. (2018) included multiple stakeholders in the decision-making process for prioritizing invaded areas across an urban landscape. Of the studies that directly assessed IAS management priorities in urban areas, 64% assessed negative impacts and 46% assessed both negative impacts and benefits of IAS. The most studied taxa are those with known significant impacts on human health (Asian Tiger Mosquito), ecosystem functioning (Emerald Ash Borer), and biodiversity (Domestic Cat).

What and where to manage: prioritization

Forty-three percent (n = 32) of studies had implications (at varying degrees of applicability) for the prioritization of aspects related to IAS in urban areas: 41% had broad implications for IAS prioritization in urban areas; 31% prioritized invaded areas for management; 16% prioritized invasive taxa for management; 9% assessed stakeholder priorities for IAS management; and 3% prioritized pathways of introduction and vectors of IAS spread (Table 1). Only 31% (n = 10) of these studies directly assessed IAS management priorities in urban areas (Table 1). Various prioritization approaches were used, including Bayesian modelling techniques, field surveys, global literature reviews, multi-criterion decision-support models, and social surveys.

When to manage: management thresholds

Only 8% (n = 6) of all studies explicitly referenced a threshold or decision trigger when developing management approaches for invasions in urban areas. These studies took place in Australia, Kenya, New Zealand, South Africa, and the USA (Table 2). All studies that applied thresholds for managing invasions in urban areas provide direct management recommendations – four of these six studies evaluated

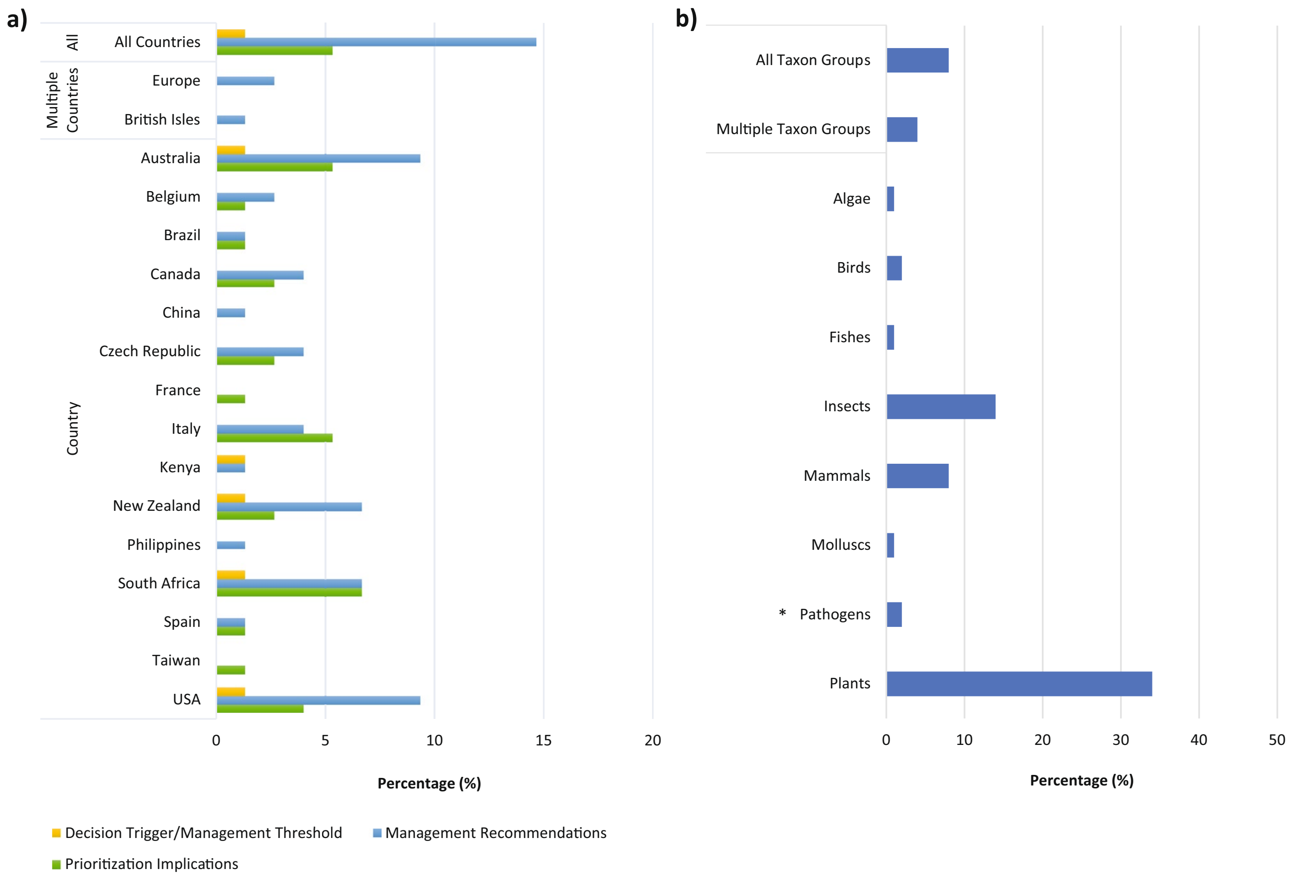

Fig. 4 **a**) Proportion of studies which provide prioritization, recommendations and/or thresholds for the management of biological invasions in urban areas around the world (note the difference in spatial scale), and **b**) taxonomic groups assessed (multiple taxon groups = two or more taxonomic groups assessed). *An organism causing disease to its host (Pirofski and Casadevall 2012). These include bacteria, fungi, prions, protozoa, viroids, or viruses

the negative impacts associated with invasions in urban areas (on biodiversity and ecosystem functioning, and/or ecosystem services), while only one study also assessed the benefits provided by IAS in urban areas. Four of the six studies used IAS density/abundance data to inform the management thresholds applied, while the remaining two studies used species richness metrics or basic reproductive number (R_0), a threshold quantity determining pathogen invasion success and outbreak size.

How to manage: management recommendations

Almost three-quarters (n = 53) of the studies provided IAS management recommendations. Just under a third of these studies had broad implications for IAS management in urban areas, 25% recommended priorities for IAS management, 17% developed a framework for use in IAS management, and one study presented a novel management tool (utilizing live, insecticide-treated termite prey) for the control of *Brachyponera chinensis* (Asian needle ant) (Buczkowski 2017; Table 1). Only 28% provided actionable management recommendations; for example, in evaluating feral cat management options in the USA, Loyd and DeVore (2010) recommended Trap-Neuter-Release as the optimal management strategy for small local populations of fewer than 50 cats (per 2.5 km^2), whereas Trap-Euthanize would be the optimal management decision for populations with more than 50 cats.

Discussion

While effective management of biological invasions relies on adequate resources and ecological knowledge of IAS and recipient ecosystems, a less-recognized barrier to IAS control is the increasingly complex social landscape in which biological invasions occur (Epanchin-Niell et al. 2010). Urban environments represent a highly complex management mosaic and the stark differences in social, ecological, and economic features compared to rural or natural landscapes indicate that novel, integrated approaches to

Table 1 Studies that had implications for the management of biological invasions in urban areas

Country/Region	What is being prioritized?	Taxon Group (Taxon)	Management Recommendation	Stakeholder Engagement	Negative Impacts	Benefits	Reference
All Countries	N/A	(Multiple) Pathogens	Specific actions recommended	No	No	No	Becker et al. (2015)
	N/A	*Maconellicoccus hirsutus* (Insect)	Specific actions recommended	No	Yes	No	Chong et al. (2015)
	Management goals	*Acridotheres tristis* (Bird)	None	No	No	No	Cohen et al. (2019)
	N/A	Multiple (Plants)	Broad implications for IAS management	No	Yes	Yes	Dickie et al. (2014)
	N/A	*Felis catus* (Mammals)	Specific actions recommended	No	Yes	Yes	Doherty et al. (2014)
	N/A	*Aedes* species (Insects)	Framework developed for use in IAS management	No	No	No	Dusfour et al. (2019)
	N/A	Multiple (Plants)	Specific actions recommended	No	Yes	No	Huebner et al. (2012)
	N/A	Multiple (All)	Framework developed for use in IAS management	No	No	No	Irlich et al. (2017)
	Conservation action	Multiple (Plants)	None	No	No	No	Kowarik and von der Lippe (2018)
	N/A	Multiple (All)	Framework developed for use in IAS management	No	Yes	Yes	Oertli and Parris (2019)
	Pathways of introduction and vectors of spread	Multiple (All)	Priorities recommended for IAS management	No	No	No	Padayachee et al. (2017)*
	IAS management based on ecosystem service and dis-services	Multiple (All)	Framework developed for use in IAS management	No	Yes	Yes	Vaz et al. (2017)
Europe	N/A	*Fallopia japonica* (Plant)	Framework developed for use in IAS management	No	Yes	No	Majorošová (2016)
	N/A	*Robinia pseudoacacia* (Plant)	Specific actions recommended	No	Yes	Yes	Vítková et al. (2017)
British Isles	N/A	*Robinia pseudoacacia* (Plant)	Specific actions recommended	No	Yes	Yes	Cierjacks et al. (2013)
Australia	Alien plant management activities to conserve biodiversity and cultural values	Multiple (Plants)	Priorities recommended for IAS management	No	No	No	Gosper et al. (2015)*
	N/A	Multiple (Plants)	Broad implications for IAS management	Yes[4,5,6,8,10]	No	No	Mumaw and Bekessy (2017)
	Areas under threat from invasion (and other threats)	Multiple (Plants)	Priorities recommended for IAS management	Yes[2,5]	Yes	No	Pert et al. (2012)
	Urban resident's behaviour to reduce the impact of wild dogs	*Canis lupus* (Mammal)	Broad implications for IAS management	Yes[4,5,10]	Yes	No	Please et al. (2018)*
	Management of *P. undulatum* in urban bushland	*Pittosporum undulatum* (Plant)	Priorities recommended for IAS management	No	No	No	Rose (1997)

Table 1 (continued)

Country/Region	What is being prioritized?	Taxon Group (Taxon)	Management Recommendation	Stakeholder Engagement	Negative Impacts	Benefits	Reference
	N/A	*Pittosporum undulatum* (Plant)	Priorities recommended for IAS management	No	Yes	No	Rose and Fairweather (1997)
Belgium	N/A	Multiple (Plants)	Broad implications for IAS management	No	No	No	Godefroid (2001)
	Management effort and resources	*Psittacula krameri* (Bird)	Broad implications for IAS management	No	Yes	No	Strubbe et al. (2010)
Brazil	IAS for management	Multiple (Plants)	Priorities recommended for IAS management	No	No	No	Petri et al. (2018)*
Canada	N/A	*Agrilus planipennis* (Insect)	Specific actions recommended	No	No	No	Grimalt et al. (2011)
	Stakeholder priorities	*Vincetoxicum rossicum* (Plant)	Broad implications for IAS management	Yes[1,8,9]	Yes	Yes	Livingstone et al. (2018)*
	Sites susceptible to invasion	*Agrilus planipennis* (Insect)	Priorities recommended for IAS management	No	No	No	Yemshanov et al. (2019)
Czech Republic	IAS for prevention, monitoring, and management	Multiple (Multiple)	Specific actions recommended	No	Yes	No	Pergl et al. (2016)
	Sites of community importance within a Protected Area	Multiple (Plants)	Broad implications for IAS management	No	No	No	Vardarman et al. (2018)
	N/A	*Scolytus intricatus* (Insect)	Specific actions recommended	No	No	No	Véle and Horák (2018)
France	Strategies to control the arrival and spread of IAS	*Harmonia axyridis* (Insect)	None	No	No	No	Veran et al. (2016)
Italy	Management strategies that include habitat conservation at the local scale	Multiple (Molluscs)	None	No	No	No	Barbato et al. (2017)
	Areas for control of Eastern Grey Squirrel	*Sciurus carolinensis* (Mammal)	Priorities recommended for IAS management	No	No	No	La Morgia et al. (2017)*
	Public mosquito control measures in temperate cities	*Aedes albopictus* (Insect)	Priorities recommended for IAS management	No	No	No	Manica et al. (2016)
	Strategies for controlling the establishment of IAS	*Caulerpa cylindracea* (Algae)	Broad implications for IAS management	No	Yes	Yes	Tamburello et al. (2015)
Kenya	N/A	*Lantana camara* (Plant)	Broad implications for IAS management	No	Yes	Yes	Furukawa et al. (2011)
New Zealand	N/A	*Trichosurus vulpecula* (Mammal)	Broad implications for IAS management	No	No	No	Lustig et al. (2019)
	Areas for hedgehog control	*Erinaceus europaeus* (Mammal)	Broad implications for IAS management	No	Yes	No	Nottingham et al. (2019)
	N/A	Multiple (Plants)	Specific actions recommended	No	Yes	No	Wallace et al. (2017)
	N/A	*Linepithema humile* (Insect)	Priorities recommended for IAS management	No	Yes	No	Ward et al. (2010)

Table 1 (continued)

Country/Region	What is being prioritized?	Taxon Group (Taxon)	Management Recommendation	Stakeholder Engagement	Negative Impacts	Benefits	Reference
	Conservation action or control of IAS	*Polistes chinensis antennalis* (Insect)	None	No	Yes	No	Ward and Morgan (2014)
Philippines	N/A	Multiple (Plants)	Specific actions recommended	No	Yes	No	Ragas et al. (2019)
South Africa	Species in rest camps and staff gardens for removal	Multiple (Plants)	Framework developed for use in IAS management	No	No	No	Foxcroft and Richardson (2003)
	N/A	Multiple (All)	Framework developed for use in IAS management	Yes[1,5,7]	Yes	Yes	Gaertner et al. (2016)
	Species with low or no benefits and a high potential for negative impacts	Multiple (All)	Framework developed for use in IAS management	Yes[1,5,7]	Yes	Yes	Gaertner et al. (2017)*
	Areas for restoration after invasive plant control	Multiple (Plants)	Priorities recommended for IAS management	Yes[3,5,6]	Yes	Yes	Mostert et al. (2018)*
	Invaded areas at city and site level	Multiple (Plants)	Priorities recommended for IAS management	Yes[3,5,6]	Yes	Yes	Potgieter et al. (2018)*
	Management of invasive plants based on stakeholder perceptions	Multiple (Plants)	Broad implications for IAS management	Yes[1,3,5,8,9]	Yes	Yes	Potgieter et al. (2019a)
	Areas based on the ecosystems services and disservices provided by alien and invasive plants	Multiple (Plants)	Priorities recommended for IAS management	No	Yes	Yes	Potgieter et al. (2019b)*
Spain	Areas rich in native and alien species	Multiple (Multiple)	Broad implications for IAS management	No	No	No	Carpio et al. (2017)
Taiwan	Management of alien species in urbanized wetlands	Multiple (Multiple)	None	No	Yes	Yes	Yam et al. (2015)
USA	N/A	*Lymantria dispar* (Insect)	Framework developed for use in IAS management	No	Yes	No	Bigsby et al. (2014)
	N/A	*Brachyponera chinensis* (Insect)	Novel management tool	No	No	No	Buczkowski (2017)
	Prioritize regional-scale monitoring and control efforts	*Ligustrum sinense* (Plant)	None	No	No	No	Davis et al. (2016)
	N/A	Multiple (Plants)	Broad implications for IAS management	No	No	No	Ehrenfeld (2008)
	Conservation and cat population management	*Felis catus* (Mammal)	None	No	No	No	Elizondo and Loss (2016)
	N/A	*Aedes albopictus* (Insect)	Specific actions recommended	Yes[9]	No	No	Fonseca et al. (2013)
	Prioritize invasive stands of Phragmites	*Phragmites australis* (Plant)	None	No	No	No	Lambert et al. (2016)

Table 1 (continued)

Country/Region	What is being prioritized?	Taxon Group (Taxon)	Management Recommendation	Stakeholder Engagement	Negative Impacts	Benefits	Reference
	N/A	*Myriophyllum spicatum* (Plant)	Broad implications for IAS management	No	Yes	No	Olden and Tamayo (2014)
	N/A	*Anoplophora glabripennis* (Plant)	Specific actions recommended	Yes[1,2,3,4,5,7,8,9]	No	No	Palmer et al. (2014)

Type of stakeholder engagement according to Shackleton et al. (2019) – [1]Assessing knowledge and perceptions of IAS; [2]Improve scientific understanding; [3]Informing policy and management planning; [4]Taking part in collaborative research, management, and citizen science (volunteers); [5]Facilitating implementation of management decisions; [6]Building cohesion and consensus; [7]Reducing/resolving conflict; [8]Understanding the effects of IAS on stakeholders; [9]Awareness and education; [10]Behavioural change

N/A means that the study did not directly assess IAS management priorities in urban areas, but rather had general IAS prioritization implications

*Studies in which priorities for IAS management in urban areas are directly assessed

managing IAS in urban areas are needed (Gaertner et al. 2016, 2017). Our review indicates that the ways in which IAS management is prioritized in urban areas, and the application of management thresholds informing the decision-making process, are still poorly understood, and biased in several ways.

Geographic distribution and scale of studies

The geographic distribution of studies included in our analysis showed that most research on prioritization, thresholds, and recommendations for urban IAS management originated from Australia, New Zealand, South Africa, and the USA (Fig. 3a). This is consistent with general trends in the history of and policymaking for the management of alien species. Simberloff (2006) noted that biological invasions as an important phenomenon to be managed were first widely recognized in these same four countries. These countries also have a long history of alien species' invasions, some of which have had major impacts early on, such as European rabbits in Australia (Williams et al. 1995), rats in New Zealand (Atkinson 1973), Australian acacias in South Africa (Macdonald and Richardson 1986), and chestnut blight in the USA (Anagnostakis 1987). IAS management in some of these countries is also driven by robust legislative and policy frameworks (Williams and West 2000; Irlich et al. 2017; Hulme 2020), such as Regional Pest Management Strategies that operate through the Biosecurity Act 1993 in New Zealand, and the Alien and Invasive Species Regulations promulgated under the South African National Environmental Management: Biodiversity Act (No. 10 of 2004). In 2017, South Africa published the world's first comprehensive national-scale assessment of the status of biological invasions and their management (van Wilgen and Wilson 2018). These countries have also developed IAS management plans for many of their towns and cities, including the Brisbane IAS Management Plan in Australia, the City of Cape Town IAS Strategy in South Africa, and the City of Richmond (VA) Invasive Species Action Plan in the USA. Legislation, research, and on-the-ground management are also complemented by education programs about the impact and control of IAS. Yet, complex management mosaics have been shown to impede IAS control in many regions of the world, including Australia and New Zealand (Williams and West 2000), and the USA (Hershdorfer et al. 2007).

Much of Africa, Asia, and South America are understudied in the context of managing biological invasions in urban areas (Fig. 3a). This geographical bias in English publications reflects the same pattern in the invasion ecology literature overall (e.g., Pyšek et al. 2008), as well as in urban biodiversity research (Aronson et al. 2016). While this could be a result of low research intensity in these regions, lower levels of invasion, or fewer policies for IAS control, it should

Table 2 Threshold metrics used in studies that apply thresholds for managing biological invasions in urban areas

Taxon Group	Taxon	Scale	Country	Threshold Metric	Reference
Pathogens	Multiple	Global	All	Basic Reproduction number (R_0) – a threshold quantity determining whether a pathogen can invade a host population. Pathogen invasion threshold ($R_0=1$)	Becker et al. (2015)
Insects	*Aedes albopictus*	County	USA	Nuisance (utility) threshold – average of ≥ 5 *A. albopictus* (male + female) adults detected during weekly surveillance	Fonseca et al. (2013)
Plants	Multiple	National Park	South Africa	1) Areas evaluated for the number of species present and densities of all alien species. For each (density and species), a score was allocated and then combined to provide the threat index for that region or river 2) Thresholds of Potential Concern (TPCs) – a diverse set of indicators	Foxcroft and Richardson (2003)
Plants*	*Lantana camara*	Urban forest	Kenya	Ecological threshold of an understory forest community – the level of disturbance at which ecological conditions change abruptly and nonlinearly	Furukawa et al. (2011)
Plants	Multiple	Regional	Australia	Composite anthropogenic threat index for native vegetation	Pert et al. (2012)
Plants	Multiple	Urban forest	New Zealand	Threshold response of ecosystem properties during ecological restoration	Wallace et al. (2017)

8% of studies applied a threshold for managing IAS in urban areas

*An ecological threshold is different to a management threshold and decision trigger (Fig. 2) – ecological thresholds are not a prerequisite for decision triggers

be noted that our review captured only peer-reviewed publications in English, which might partly explain the disparity. This geographic bias distorts our understanding of management approaches for invasions in urban areas, as important insights are not included from non-English information sources or practitioners in understudied towns and cities.

Invasive taxa and their impacts

Plants and insects accounted for almost two-thirds of the taxa studied – a taxonomic bias supported by Pyšek et al.'s (2008) analysis of the study of invasions overall. The emphasis in the literature on the management of invasive insect and plant taxa might reflect their relative abundance and impact in urban areas due to, for example, high levels of widespread plantings and/or invasions, ease of identification, or lack of mobility.

An assessment of the impacts of IAS in urban areas can be used as a means of setting management thresholds and priorities (Fig. 1). These impacts tend to increase along the introduction-naturalization-invasion continuum and can manifest in different ways, affecting various aspects of the socio-ecological system (see ecosystem cascade model by Haines-Young and Potschin 2010). The realized or perceived impact of a species often determines whether it is studied (Pyšek et al. 2008). The nature and scale of the impacts of the most studied taxa (Tiger Mosquito, Emerald Ash Borer, and Domestic Cat), and the complex management methods associated with them, likely justify their research emphasis, but they are not the only IAS with significant impacts in urban ecosystems. Few studies assessed the impacts of invasions in urban areas (e.g., on biodiversity, ecosystem functioning, or ecosystem services; Table 1). Generally, robust and comparable data on the impacts of alien species in different regions remain scarce. Describing and quantifying impacts are notoriously difficult, particularly in urban areas (Potgieter and Cadotte 2020), and as a result, significant uncertainties in impact assessments remain (Simberloff et al. 2013). Other factors can further complicate impact assessments in urban areas, which makes efforts to lobby for funding to manage invasions difficult. The number of different land parcels and diversity of stakeholders in an urban area means that impacts can be highly context-specific and subjective (value-laden), often leading to conflicts over IAS management (Dickie et al. 2014; Potgieter et al. 2019a, 2020). For example, attempts to control domestic cat populations around the world have been met with substantial public backlash, particularly in urban areas, requiring practitioners to develop effective non-lethal control methods (Loyd and DeVore 2010; Woolley and Hartley 2019). Impacts of IAS realized in urban areas might also originate outside urban boundaries; determining the source and extent of the impact and the ability to manage source populations on land parcels under different jurisdictions can be problematic (Irlich et al. 2017). This lack of information and the resources (e.g., funding and time) required to obtain it, hinders attempts to integrate thresholds and decision triggers into management frameworks.

Prioritization

Effective prioritization for IAS management requires a consultative, evidence-based process for prioritizing impacts based on species, pathways, and sites that incorporates a broad suite of economic, environmental, and social criteria (Fig. 1; McGeoch et al. 2016). Less than half of the studies with implications for prioritizing IAS management assessed negative impacts of invasions in urban areas (on biodiversity and ecosystem functioning, and/or ecosystem services) and less than a third examined the benefits associated with IAS (Table 1). Moreover, only a third of studies with implications for prioritizing IAS management directly assessed priorities in urban areas (Table 1). It is unclear to what degree, if at all, studies with prioritization implications are used to inform the development of prioritization schemes or allocation of resources for IAS management. Less than a third of such studies include stakeholder views in their assessments, suggesting that the prioritization of IAS management in urban areas is influenced by judgements that are either primarily based on inputs from scientists, or solely on practitioners' knowledge and experience. This could also reflect the substantial resource investment required to complete stakeholder assessments (Novoa et al. 2017).

Several studies have developed approaches for establishing priorities for IAS management in urban areas. For example, Potgieter et al. (2018) used multi-criteria decision tools to develop a multi-scale prioritization framework for managing invaded sites at landscape and local scales across Cape Town, South Africa. Other more generalized prioritization schemes (not specific to urban areas and thus not captured in our search) have been developed for IAS. For example, Kumschick et al. (2012) provided a framework for the prioritization of invasive alien plants for management according to both their positive and negative impacts. This framework includes both a scientific impact assessment and the evaluation of impact importance by affected stakeholders. However, more work is needed to determine whether these frameworks can be applied, adapted, or modified to fit urban landscapes around the world and be usable by different actors (e.g., conservation practitioners, city planners, scientists) at different spatio-temporal scales.

Management thresholds and decision triggers

Few studies apply management thresholds that could be used to trigger action when managing IAS in urban areas (Table 2). This suggests that most management decisions are made on an ad hoc basis, or that decision triggers are prompted by external factors that are not reported in the formal literature, such as funding mandates, public pressure, lack of public support, or operational challenges (e.g., site accessibility, security). For example, informal utility thresholds could be used, where action is taken when the number of public complaints reaches a particular level (Irlich et al. 2017). There are challenges for both developing management thresholds and implementing decision triggers, and there will be occasions where decision triggers cannot be implemented. Some key barriers to formalizing management thresholds and decision triggers include incomplete ecological knowledge (e.g., the relationship between drivers, pressures, and ecosystem states), inflexible and insufficient funding, inadequate quality/quantity of monitoring data, and staffing limitations (Addison et al. 2016; Foster et al. 2019). Urban conservation practitioners frequently make decisions under uncertainty and do not necessarily require complete information to carry out management actions (i.e., use best available information) (Foster et al. 2019). In their study of protected areas in Australia, Cook et al. (2010) found that very few conservation practitioners use empirical evidence to support their management, and most conservation management decisions rely on experience-based information. Our results suggest that this might also be the case for many conservation practitioners.

Integrating indicators (ecological, economic, or social) into management planning (e.g., ecosystem service indicators; Qu and Lu 2018) can provide a means to select the best sites or times for management actions that assist practitioners in meeting their objectives. Indeed, defining management thresholds and associated triggers for action *a priori* for indicators rather than reacting to unexpected ecosystem changes is likely to be a more proactive and effective approach to management (Addison et al. 2015). For decision triggers to be effective, there must be a commitment to ongoing monitoring of relevant and practical indicators (de Bie et al. 2018). A lack of robust and reliable monitoring data can impede the adoption and implementation of decision triggers (Addison et al. 2016). Quantitative data on the impacts of IAS in urban areas remain scarce and this complicates attempts to develop indicators to inform management thresholds. Moreover, it is difficult to determine the point at which an IAS moves from one invasion stage to another, further complicating attempts to set management thresholds. However, when monitoring data are not readily available, there are approaches to set decision triggers using value-based judgements or expert elicitation methods (Cook et al. 2016).

Decision triggers can be informed by ecological thresholds, assisting practitioners to avoid undesirable shifts in ecosystems. The inherent complexity of urban systems means that ecological thresholds can be difficult to identify or absent from the system. Identifying thresholds of potential concern (TPCs) is one approach that has been used (e.g., in national parks in South Africa) to identify when management intervention should occur (Biggs and Rogers 2003). These TPCs represent the upper and lower limits of acceptable change in ecosystem structure, function, and composition over time and at a specified spatial scale (Foxcroft 2009). Themes of TPCs defined for IAS include: 1) distribution; 2) increases in density; 3) rate of spread versus rate of clearing; 4) impact on biodiversity; and 5) outside alien threats (Foxcroft and Richardson 2003). A TPC is reached when one or more of these limits are exceeded. However, this approach relies on ecological indicators to inform management thresholds in isolation of competing socio-economic factors. This can be useful in contexts where ecological objectives are the sole driver of conservation efforts. However, in urban areas decisions must be made amid competing and often conflicting environmental, social, and economic objectives (Game et al. 2013), and decision triggers associated with utility thresholds might be more appropriate.

Lack of applicable management recommendations

Considerations affecting IAS management can be highly context-dependent (González-Moreno et al. 2014), especially in urban areas where complex land-tenure patterns and smaller, more numerous land parcels with individual actors managing them influence the management context. The spatial scale at which a study is conducted reflects the scale at which the management recommendations are applicable. Almost three-quarters of studies in our analysis provide some form of IAS management recommendations but they differed considerably in the applicability of these recommendations. Some studies provide detailed species-specific practical recommendations (e.g., Chong et al. 2015), decision trees assigning species to management categories (e.g., Gaertner et al. 2016), or management frameworks (e.g., Potgieter et al. 2018). However, many studies offer no conservation or management recommendations and simply suggest that the study's findings have management implications or can generally be used to prioritize IAS management – a broader problem in the conservation literature (Fazey et al. 2005).

Limitations

Reviewing subject matter that is applied and practitioner-focused should incorporate searchable examples outside of the peer-reviewed scientific literature (e.g., white papers, technical reports, and examples from city websites). However, in the absence of discoverable, searchable grey literature databases, it has been difficult to formally integrate grey literature into systematic reviews. New online, open-access information hubs such as AER can significantly bolster future systematic reviews. While this database is a recent innovation and currently lacks a critical mass of material, applying our search criteria to this database yielded no results.

Including non-English sources into systematic reviews can alleviate bias, enhance data completeness, and reduce knowledge gaps (Angulo et al. 2021). We recognize that our review likely missed some important contributions and insights from less accessible journals and from the grey literature, especially publications in languages other than English, but we are confident that the collection of publications included in our analysis provides an appropriate sample for a broad overview and to draw reliable conclusions on recent approaches to managing biological invasions in urban areas.

Conclusions

Our review indicates that the ways in which IAS management is prioritized in urban areas, and the application of management thresholds informing the decision-making process, are still poorly understood, and biased in several ways. This might suggest the implementation of less formal or structured approaches to managing IAS in urban areas (i.e., without considering explicit, objective, and transparent criteria), or that IAS management in urban areas is triggered by external factors (e.g., funding availability) that are not recorded in the formal literature.

Existing management, evaluation, and conservation planning frameworks can inform how the development and implementation of management thresholds and associated decision triggers align with evidence-based decision-making, such as adaptive management, and structured decision-making (de Bie et al. 2018). Structured decision-making can assist with setting management thresholds for multi-objective decisions (Martin et al. 2009). It shows potential for application to IAS in urban areas as it incorporates both scientific knowledge and values into decision-making and promotes the involvement of multiple stakeholders in the decision-making process (Gregory et al. 2012). More work is needed to determine the applicability of such frameworks.

Robust impact assessments (including positive and negative impacts) are key considerations in developing urban-specific prioritization approaches and evidence-based thresholds for managing IAS in urban areas. Facilitated by comprehensive stakeholder engagement, defensible decisions can be made about what, where, and when IAS management is required in urban areas.

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