



Managing Urban Plant Invasions: a Multi-Criteria Prioritization Approach

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Abstract

Alien plant invasions in urban areas can have considerable impact on biodiversity and ecosystem services (ES). Managing urban plant invasions is particularly challenging given the complex interactions between ecological, economic and social elements that exist in the urban milieu. Strategic landscape-scale insights are crucial for guiding management, as are tactical site-scale perspectives to plan and coordinate control efforts on the ground. Integrating these requirements to enhance management efficiency is a major challenge. Decision-support models have considerable potential for guiding and informing management strategies when problems are complex. This study uses multi-criteria decision tools to develop a prioritization framework for managing invasive alien plants (IAPs) in urban areas at landscape and local scales. We used the Analytic Hierarchy Process (AHP; a multi-criteria decision support model) to develop and rank criteria for prioritising IAP management in the City of Cape Town (CoCT), South Africa. Located within a global biodiversity hotspot, Cape Town has a long history of alien plant introductions and a complex socio-political make-up, creating a useful system to explore the challenges associated with managing urban plant invasions. To guide the prioritization of areas for IAP management across the CoCT, a stakeholder workshop was held to identify a goal and criteria for consideration, and to assess the relative importance given to each criterion in IAP management. Workshop attendees were drawn from multiple disciplines involved with different aspects of IAP research and management: government departments, scientists and researchers, and managers with a diverse set of skills and interests. We selected spatial datasets and applied our multi-criteria decision analysis in a Geographic Information System (GIS) to develop a landscape-scale prioritization map. To address issues relevant in an urban setting, we also modified an existing IAP management framework to develop a tactical (site-level) prioritization scheme for guiding on-the-ground control operations. High-priority sites for IAP management were identified at landscape- and local scales across the study area. Factors related to safety and security emerged as pivotal features for setting spatially-explicit priorities for management. The approach applied in this study can be useful for managers in all urban settings to guide the selection and prioritization of areas for IAP management.

Keywords Biological invasions · Ecosystem services · Invasive alien plants · Multi-criteria analysis · Prioritization · Urban ecosystems

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Introduction

In an increasingly human-dominated world, biodiversity and ecosystem services (ES) are threatened not only by the

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expansion of urban areas and the proliferation of anthropogenic features that drive land-cover change, but also by invasive species (Aronson et al. 2014; Zhou et al. 2015). Invasive alien species in human-dominated environments pose threats to infrastructure, property, and the lives and livelihoods of communities in many ways. For example, invasive alien plants (IAPs) increase the frequency and severity of fires, exacerbate the impacts of floods, and (especially in developing countries) can serve as hiding places for people engaged in criminal activity, ultimately compromising the safety of communities (Allsopp et al. 2014).

Management of IAPs is needed to alleviate such negative impacts (van Wilgen et al. 1994, 1998; Wilson et al. 2013). However, managing IAPs in urban areas is particularly challenging due to the diversity in the landscape, land use, mandates, threats and pressures, and existing management frameworks and paradigms for dealing with urban plant invasions are inadequate for guiding effective and sustainable interventions (Gaertner et al. 2016, 2017). The challenges are compounded where urban areas adjoin or enclose regions of high conservation value, when actions required to safeguard biodiversity may conflict with those deemed appropriate for requirements of urban residents. For example, managing urban plant invasions often requires deviation from the standard approach of prioritising less dense areas over dense areas (which is most cost-effective and beneficial in preventing impacts; Higgins et al. 2000) - dense stands of IAPs pose immediate risks in terms of fire, and safety and security and must often be prioritized. Managers frequently also need to deviate from strategic plans based on cost-effectiveness and biodiversity considerations to accommodate prioritisation for socio-political reasons (e.g., public complaints). Such considerations often draw attention away from areas of high conservation value and reduce the overall efficiency of actions in achieving long-term aims.

Additional barriers hindering the effective management of urban plant invasions include funding insecurity, inadequate management capacity (uncertain mandates and uncoordinated management), and a lack of effective monitoring (especially due to the lack of detailed and up-to-date data on the distribution of IAPs) (Table 1). Control efforts may also be disrupted, especially when applied to areas under multi-purpose management, due to misaligned or conflicting management mandates (Gaston et al. 2013). Added pressures from communities and political agendas further shape management decisions. Such challenges are particularly complex in developing countries where inefficient resources and land use leads to negative environmental consequences and negative social impacts in the long term (Piracha and Marcotullio 2003). Managing urban plant invasions therefore requires a strategic approach to guide management across the urban landscape, and a tactical approach to plan and coordinate control efforts on the

Table 1 Barriers affecting the allocation of resources for invasive alien plant management in the City of Cape Town, South Africa

Barriers	Description	Source
Conflicting priorities	Available budget allocated to 'higher priority' issues such as housing development and service delivery.	Ruwanza and Shackleton (2016)
Finance	Budget cuts; ineffective planning and budgeting.	Ruwanza and Shackleton (2016)
Enforcement	Lack of enforcement of legislation.	Cronin et al. (2017)
Awareness/knowledge	Awareness of invasive species impacts is generally poor, and knowledge of the relevant legal requirements pertaining to invasive species is lacking.	Irllich et al. (2017)
Political will	Lack of political buy-in and support for particular interventions.	Nunan et al. (2012)
Interest	Lack of interest within local government constituencies for environment-related issues.	Ruwanza and Shackleton (2016)
Capacity and skills	Lack of capacity and skills to develop, implement, monitor and report on invasive species management.	Irllich et al. (2017)
Information	Lack of detailed and up-to-date data on the distribution and impact of invasive species, fire histories and other key environment factors.	Roura-Pascual et al. (2009)
Government structures	Depending on the local government structures, different functions or departments are responsible for managing different parcels of land. Departments have different mandates, access to resources, and varying expertise in managing invasive species, while some are not structured or mandated to perform their environmental responsibilities at all.	Irllich et al. (2017)
Integration into existing plans and strategies	Current invasive species strategies and management plans have yet to be fully integrated into existing governmental plans.	Ruwanza and Shackleton (2016)

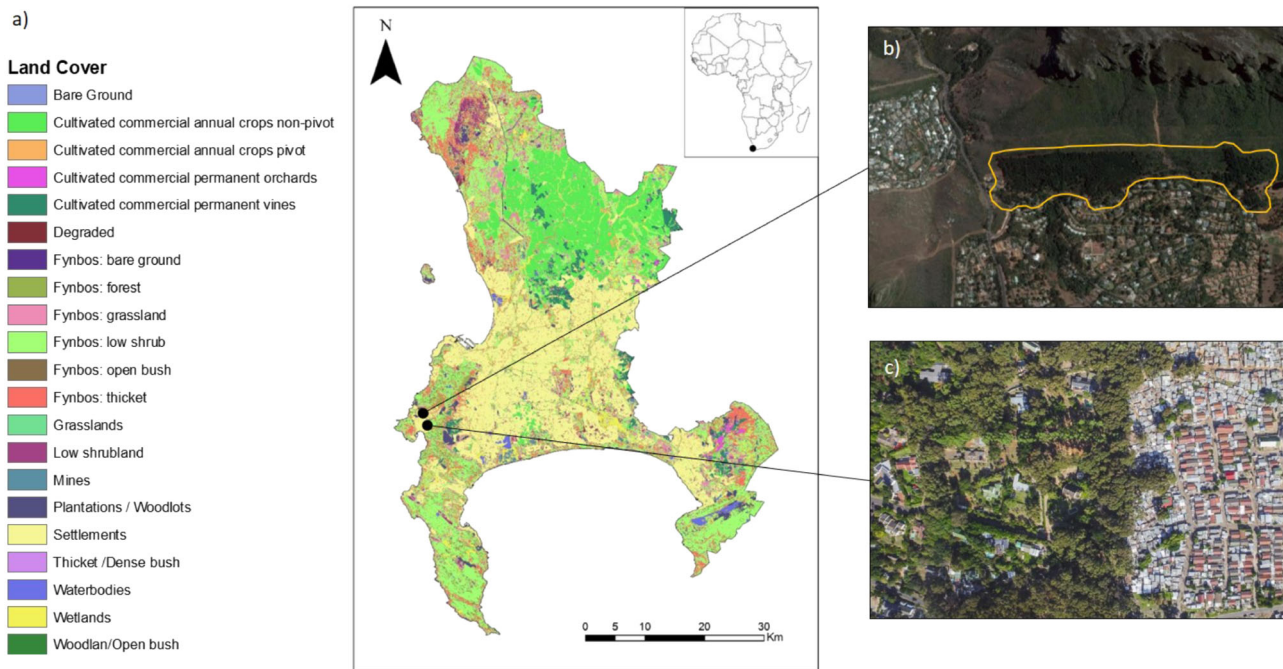


Fig. 1 **a** Location of the City of Cape Town, South Africa, showing land cover (2013/2014), data from Department of Environmental Affairs (2016). **b** Stands of alien trees bordering residential properties (Hout Bay) invade the fire-prone fynbos vegetation, Photo: Google

c Spatial inequality in the City of Cape Town (affluent housing estate adjoining a high-density informal settlement, Hout Bay), Photo: Johnny Miller

ground. The challenge is to integrate these perspectives into a unified framework.

An efficient prioritisation strategy for IAP management is one that distributes resources in time and space in a way that results in the greatest progress from the resources available (Grice 2000). Decisions on managing IAPs are often informal (i.e., based on experience, ad hoc consultation, or short-term opportunities or emergencies), or are based on regional species-level rankings (Fox and Gordon 2009), or legal requirements (Gaertner et al. 2016). They thus seldom give full consideration to local perspectives (e.g., public opinion). This approach to decision-making potentially squanders resources and fails to address the range and spatial variability of IAP impacts. Management approaches for urban plant invasions are often confounded, and in some cases disrupted, by conflicts of interest that arise when the ES provided by alien plants are weighed against the ecosystem disservices provided by the same species (Dickie et al. 2014; Gaertner et al. 2016; Potgieter et al. 2017). Such conflicts exemplify the extent to which IAP management, especially in human-dominated areas, is increasingly viewed as a “wicked problem” (*sensu* Rittel and Webber 1973) as there are seldom straightforward “win-win” solutions. The key challenge in prioritizing areas for IAP management in such situations is to integrate ecological, economic, conservation, and social needs into a comprehensive management strategy that includes multiple

considerations across the entire urban matrix (Cilliers et al. 2012). Such decisions must be transparent and should consider opinions, perspectives and values of a wide range of stakeholders involved in urban land-use and ecosystem management decisions (De Lange et al. 2012; Forsyth et al. 2012).

We know of no guidelines for a general approach to prioritize areas for IAP management in urban systems; such insights are clearly needed to optimize investments. Climate, geography, disturbance history, and cultural factors that affect how countries and different sectors of society place value on particular sites, all contribute to the complex dynamics of urban ecosystems and ways of integrating such factors in a transparent way must be sought. Few studies have explicitly examined how spatial characteristics of a heterogeneous, urban landscape can affect IAP control strategies and how these factors need to be integrated to inform where management efforts should be applied.

This study aims to develop a dual approach for landscape-scale and site-level prioritization of IAP management in urban areas, using the City of Cape Town (CoCT), South Africa as a case study. We include multiple stakeholders in the decision-making process and provide a transparent methodology which is applicable to urban centres across different geographic regions and spatial scales. We also discuss the challenges associated with developing and implementing IAP management in urban areas. This

dual approach provides guidance on where best to focus IAP management efforts across the urban landscape and assists managers in prioritizing on-the-ground IAP control operations at the site level.

Methods

Study Area

Urban landscape

Covering 2460 km², the CoCT has a population of 3.8 million people and is growing more rapidly than any other southern African metropolis (Boraine et al. 2006). Land-use at the edges of the city includes high-density urban development and informal settlements, rural residential development, agriculture, industrial uses, and conservation (Fig. 1a). Twenty-six percent of the city's municipal area is under urban development, 35% is under agriculture, while 39% has natural and semi-natural vegetation in mountainous areas, mainly within the Table Mountain National Park (TMNP; Holmes et al. 2012). Most of the lowland areas of the city, where the bulk of the diversity of vegetation types lie, have been transformed and all (semi-natural) vegetation that remains in the lowlands is under considerable threat from further development (Holmes et al. 2012; Goodness and Anderson 2013).

Cape Town has a long history of European colonization and the associated introductions of alien plant species present significant challenges to people and the landscape (Anderson and O'Farrell 2012; van Wilgen 2012). Many residential properties along the urban edge border the fire-prone fynbos vegetation (Alston and Richardson, 2006), and the presence of IAPs pose a significant fire risk (Richardson et al. 1994) (Fig. 1b). Cape Town's urban spatial arrangement is typical of post-apartheid cities in South Africa with racially defined spatial planning still evident and aligned with significant wealth disparities (Swilling 2010; Fig. 1c). Major socio-economic challenges within the city include the provision of education, housing, nutrition and healthcare, and transport infrastructure (Goodness and Anderson 2013). Pressure to address development issues of unemployment, poverty, and the formal housing shortfall, all place considerable demand on remaining vegetation patches, which are highly sought after for conversion to housing or industrial development (Goodness and Anderson 2013). Additional pressures such as those relating to service delivery frequently divert funding away from environment-related issues (Table 1). The result is a population with diverse and often divergent needs, which shapes the demand for ES provision in the city.

Biodiversity conservation and ecosystem services

Cape Town is located at the southwestern tip of Africa, in the Cape Floristic Region (CFR) - a globally recognized biodiversity hotspot (Holmes et al. 2012). The city is home to 19 of South Africa's 435 national recognized vegetation types and hosts 52% of the country's critically endangered vegetation types (Rebello et al. 2011). The region has a Mediterranean-type climate and the indigenous vegetation, termed fynbos, is a fire-prone and fire-adapted shrubland occurring on sandy, infertile soils (Cowling and Richardson 1995). The high concentration of biodiversity within the urban matrix poses major challenges for conservation (Richardson et al. 1998).

Biodiversity plays an important role in the delivery of ES - as a regulator of underpinning ecosystem processes and as a service itself (Mace et al. 2005). Consequently, the loss of biodiversity can potentially reduce the provision of ES that are essential for human well-being and for creating sustainable urban ecosystems. Many of these services, and the biodiversity and ecological infrastructure on which they depend, have been degraded.

The CoCT's Biodiversity Strategy (2003) required, among other things, that a Biodiversity Network (BioNet) be established to enable the conservation of critical biodiversity areas (CBAs) - these are considered the minimum areas of terrestrial and freshwater habitat required to meet the city's biodiversity conservation targets (Holmes et al. 2012). The CBAs are crucial for conserving biodiversity and maintaining ecological functioning and are used to guide decision-making about where best to locate urban development. Such plans are, however, often overlooked in favour of fulfilling development and housing requirements.

Detailed case study: Kenilworth Racecourse Conservation Area, City of Cape Town, South Africa

Our strategic prioritization identified the Kenilworth Racecourse Conservation Area (KRCA) as a high priority for management based on the level of plant invasion, the rich biodiversity and its proximity to infrastructure. It therefore represents a useful case study to test our tactical prioritization approach.

KRCA is an area of 52 hectares situated in the centre of Kenilworth Racecourse and is the largest conservation area surrounded by urbanisation remaining in Cape Town's southern suburbs. It contains some of the last remnants of Cape Flats Sand Fynbos - a vegetation type of which only 14% remains. In addition to the critically endangered vegetation, the site has several wetlands (permanent and seasonal) which are of considerable ecological importance. Prescribed burns are conducted, and vegetation is actively restored, and although IAPs are actively managed, they

have yet to be completely extirpated. The many challenges associated with managing IAPs in urban areas (Table 1) may, however, impede control operations or divert the management focus to other high priority sites. For example, despite its conservation significance, the owners of the Kenilworth Racecourse (in which the KRCA is located) have received permission from the CoCT to subdivide and develop certain sections of the site - a decision which may redirect management efforts and influence strategic and tactical prioritization.

This case study underlines some of the challenges IAP managers encounter in urban areas and emphasizes the need to fulfil development requirements while attempting to meet conservation targets.

Strategic prioritization

In this study, “strategic prioritization” involves identifying and prioritizing areas for IAP management across the urban landscape. “Tactical prioritization” involves dividing these strategically prioritized areas into smaller management areas (Management Units; see Box 1) for further prioritization based on specific site-level characteristics. Tactics for IAP management refer to all possible control actions, and more importantly, the most appropriate combination of those actions that will yield the desired result.

Multi-criteria approach

Decision-support models have considerable potential for guiding management strategies when problems are complex. A multi-criteria approach using the AHP method (Saaty 1990) was applied to develop a decision-making framework for prioritising management of IAPs across the CoCT. AHP is used to determine the relative importance of factors/criteria in relation to a specific goal (Saaty 1980). Pair-wise comparisons of criteria can be made to derive accurate ratio-scale priorities, as opposed to the traditional approach of assigning single weights (Saaty 1980). It has been successfully used to prioritize species and quaternary catchments for IAP control (van Wilgen et al. 2008; Forsyth et al. 2009; Roura-Pascual et al. 2009, 2010; Forsyth and Le Maitre 2011; Forsyth et al. 2012). This technique, used to synthesize information derived from stakeholders, provides an objective way of ranking the factors involved in the selection of areas for IAP management.

The selection and ranking of the factors influencing management decisions was done at a workshop hosted by the CoCT (8 April 2016) (Fig. 2). The workshop was attended by 15 stakeholders drawn from three broad groups: (1) government departments responsible for nature conservation, (2) scientists and researchers focussing on the

Box 1 Definitions and concepts relating to the prioritization framework for managing invasive alien plants (IAPs) in urban areas at landscape and local scales

Area approach: an approach used to manage areas invaded by alien plants. This differs to the species approach in which individual species are targeted for management.

Early detection and rapid response (EDRR): A management tactic aimed at managing individual invasive alien species that are detected early enough to warrant extirpation attempts. Targeted species management plans are being developed.

Follow-up treatment: consistent repeat control to prevent IAPs from flowering, until the seed bank is exhausted.

Management units (MUs): each site is divided into different manageable units (management units, MUs), based on, for example, the location of natural boundaries (rivers/streams) or infrastructure (roads, fences). Each unit is assigned an alphanumeric identification number. The rationale for dividing properties into smaller MUs is to make surveying, planning and management easier.

Size classes: a set of predefined size categories used to describe the age of IAPs (for example; ‘Seedlings’ <2 cm stem diameter; ‘Young’ 3–20 cm in diameter; ‘Mature’ >20 cm in diameter; ‘Mixed’ combination of mature, young and seedlings).

Stewardship sites: sites of critical importance for biodiversity conservation and/or the provision of ecosystem services in which a partnership between landowners and conservation organizations or departments have been established to ensure the security and appropriate management of the ecosystems.

Tactics: a site-level prioritization approach. Sites may denote parcels of land such as protected areas, public open space, vacant land, road verges, riverine areas, wetlands or clusters of different land parcels.

Workload assessments: a site assessment in which each MU is surveyed and baseline information captured. All alien species present within each MU are listed and categorised according to predefined size classes (i.e. seedlings, young, mature). The density of alien plant cover (% cover) is also estimated for each MU. If possible, clearing history is also noted. Workload assessment are used to determine the resources need to control IAPs per MU.

ecology and control of IAPs, and (3) managers responsible for the implementation of alien plant control operations. While we acknowledge the number of workshop attendees is limited, the stakeholders have significant experience in key decision-making and management positions within leading scientific authorities and governmental organisations. Including stakeholders from such diverse disciplines can also strengthen the decision model, allowing for more defensible outcomes. Prior to conducting the AHP, a presentation was given to provide stakeholders with background knowledge of the process and the aims of the workshop.

Based on the impacts identified, an overarching strategic goal for managing IAPs in CoCT was identified (Fig. 2). Criteria and sub-criteria required to achieve this goal were identified and used to construct the framework (Arroyo et al. 2015). The goal and criteria were discussed further to ensure all participants were aware of the meaning, value,

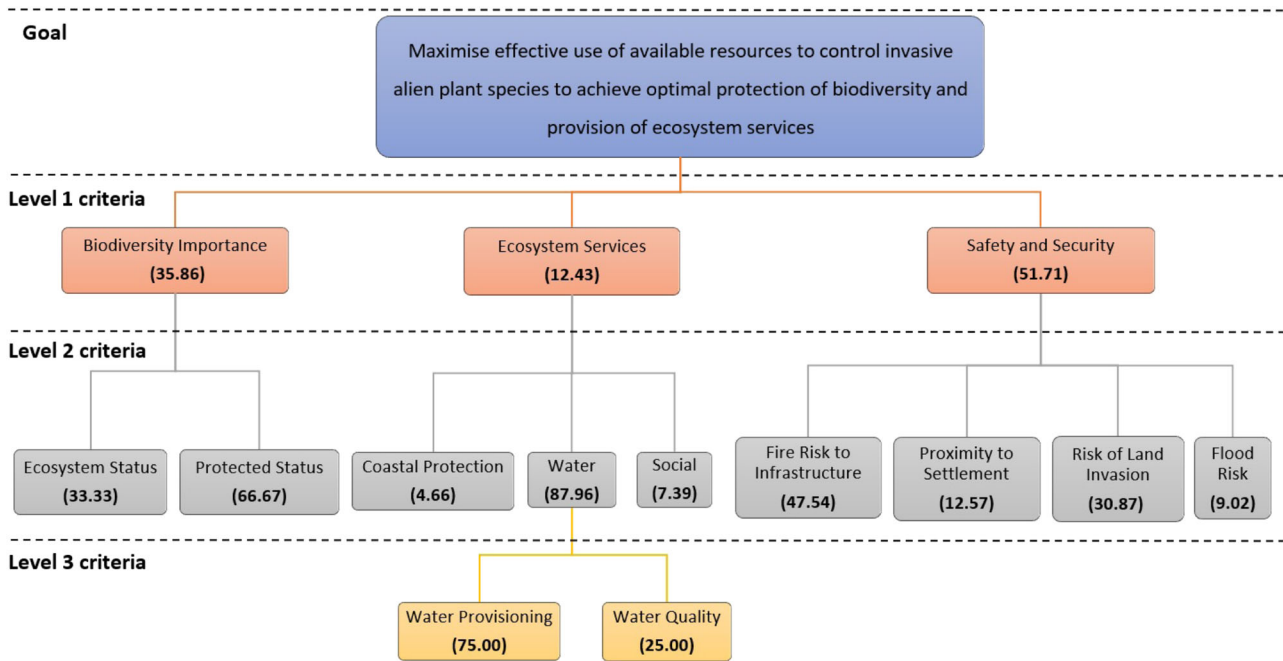


Fig. 2 Overall goal, criteria and sub-criteria of the City of Cape Town’s decision-making framework for the management of invasive alien plants, showing the relative weights (%) in bold of each criterion when compared to other criteria of the same level

and implications of each element. The advantage of group consensus is that it allows for the discussion of pairwise comparisons which, in turn, improves participants’ understanding of the problem and criteria, ensuring that participants answer less inconsistently.

Using Super Decisions software version 2.4.0, these criteria and their sub-criteria were then compared pairwise to each other to establish weightings to denote the importance of each criterion relative to one another (Arroyo et al. 2015). Variation in pair-wise judgments was examined to identify how consistent stakeholders were when comparing the relative importance of criteria. We used a consistency ratio (measure of consistency), which describes the probability that a stakeholder-provided judgment matrix differs from a randomly generated judgment matrix (Saaty 1977).

Analysis

The final weights developed by stakeholders during the workshop were assigned spatial data layers whereby each criterion and sub-criterion are assigned those layers that best represent each, e.g., vegetation type is represented by the map of remnants of indigenous vegetation within the boundaries of Cape Town (see Table 2).

The weights derived from the AHP process were applied to each spatial data layer and were aggregated using Weighted Sum Tool under the Overlay Spatial Analyst tool in ArcGIS 10.3. A weighted sum analysis provides the ability to weight and combine multiple inputs to create an

integrated analysis; it combines multiple raster inputs, representing multiple factors, of different weights or relative importance. A final map was created showing areas of high to low priority for IAP management across the CoCT.

Tactical prioritization

The tactical prioritization was based on the approach taken by Roura-Pascual et al. (2009) who applied two methodologies, namely the Driver-Pressure-State-Impacts-Response (DPSIR) framework and AHP, at several workshops with experts on woody IAP management in South Africa. DPSIR was used to identify the factors involved in prioritizing areas for management, while AHP provided an objective way of ranking these factors. Roura-Pascual et al. (2009) used this process to identify 28 main factors, which were subdivided into a smaller number of sub-factors and assigned specific weights. Factors were divided into four overarching groups: (1) species attributes, (2) stand attributes, (3) environmental context and (4) management context.

Only the factors grouped as “stand attributes” (fire history, density of IAPs, spread based on topography, fire risk, age of IAPs, identity of IAPs and last clearing operation) were considered for this prioritization. Since the scale of prioritizing management units (MUs; Box 1) within a site corresponds well with the local-scale prioritization scheme of Roura-Pascual et al. (2009), the same stand-attribute factors are appropriate for prioritizing management actions in the CoCT. Using this scheme, MUs within a site are

Table 2 Criteria and sub-criteria identified at the stakeholder workshop and the corresponding spatial data layers and data sources

Criteria	Sub-criteria	Spatial data	Data source
Biodiversity importance	Ecosystem status	Vegetation remnants; biodiversity agreement sites; Stewardship sites	City of Cape Town data portal; SANBI BGIS data portal
	Protected status	Biodiversity network (CBA rank)	Biodiversity network (2015); SANBI BGIS data portal
Ecosystem services	Coastal protection	Coastal protection zone	O'Farrell et al. (2012)
	Water (water provisioning and water quality)	Dams, aquifers, rivers	City of Cape Town data portal; invasive species unit (August 2016)
	Social	Heritage, education, tourism	O'Farrell et al. (2012)
	Fire risk to infrastructure	IAP density data	Invasive species unit (August 2016); distance of densely invaded vegetation ($\geq 75\%$) to infrastructure—calculated from layer
Safety and security	Flood risk	Aquatic sites; flood prone areas	Flood prone areas (director: disaster risk reduction); invasive species unit (August 2016)
	Proximity to settlement	IAP density data; infrastructure	Invasive species unit (August 2016); distance of densely invaded vegetation ($\geq 75\%$) to infrastructure—calculated from layer
	Risk of land invasion	Land invasion hotspots	Invasive species unit (August 2016); anti land invasion unit

prioritized according to an area approach (Box 1). Factors within the species attributes category, specifically the stand attributes factor “Identity of IAPs”, correspond with the CoCT species approach (Early Detection Rapid Response (EDRR) programme; Box 1). These factors are already considered when prioritizing individual species for control interventions and creating the EDRR target species list and were therefore not included under this area of approach. The factors grouped within the environmental context were not considered as they formed part of the strategic prioritization presented in this study. Factors within the management category were not expected to affect the final prioritization, but rather to act as constraints to IAP management, and were therefore also not considered for the prioritization of areas.

The first step in the area prioritization process was to clearly define each of the stand attribute factors. Recent fires were defined as those that occurred over the last 12 months, as this corresponds to the minimum time that most IAPs take to mature after fire (van Wilgen et al. 1994). Incidences of fire alter management priorities, as fire stimulates the regrowth of certain IAPs, e.g., *Acacia* species (Richardson and Kluge 2008). Accordingly, areas burnt in the last 12 months become a high priority for management.

Potential for spread was defined, following Roura-Pascual et al. (2009), based on the presence of wind-dispersed species on upper slopes and/or water-dispersed species in riparian areas (Table 3). Areas with a high probability of fire were defined according to the density of IAPs, the age of IAP stands, the position in the landscape and the presence of adjacent points of fire ignition. A high density of IAPs, as well as mature IAP stands, increase the amount of flammable biomass and therefore increase the fire risk in that MU, posing a threat to infrastructure and human safety. Regarding position in the landscape, the steeper the slope, the closer the fuels are to the flames, and thus the higher the risk of fire. Position on a slope also influences fuel availability, with more fuel available at the base of slope than on the top. MUs located at the bottom of a slope or in a valley have a higher fire risk (Teie 2009), while those located on mountain ridges have a lower risk of fire. MUs that adjoin residential areas or unmanaged natural areas where stands of IAPs provide shelter for illegal activities are also a higher fire risk due to the increased chance of ignition. Finally, the combination of all risk factors determines whether a MU is at a high, medium or low risk of fire (Table 3).

The IAP density sub-criteria were adjusted to correspond with the density categories used by the CoCT (Table 3). The highest management priority is given to MUs that have a low IAP density, as IAP control within these MUs requires the least resources. The scheme was updated to include the size classes used by the CoCT (see Box 1). In the case of

Table 3 Main and sub-factors and corresponding weights (adjusted accordingly) for the tactical (site-level) prioritization of management units based on the stand attribute categorisation and weightings from Roura-Pascual et al. (2009)

Main factors (stand attributes)	Weighting of main factors	Sub-factors	Weighting of sub-factors
Area burned in the last 12 months	0.4	Yes: Area burned in the last 12 months	0.9
		No: Area burned more than 12 months ago	0.1
Density of IAPs (% cover)	0.18	>75	0.06
		51–75	0.07
		26–50	0.09
		6 – 25	0.13
		1–5	0.24
Spread based on topography	0.18	<1	0.41
		Low: Neither wind-dispersed species on upper slopes, nor water-dispersed species in riparian area	0.07
		Medium: Wind-dispersed species on upper slopes OR water-dispersed species in riparian area	0.3
		High: Wind-dispersed species on upper slopes AND water-dispersed species in riparian area	0.63
Area at fire risk	0.13	Low: Density of IAP <50% AND situated on flat ground	0.07
		Medium: Density of IAP 50–75% AND situated on a gentle slope, top of slope or on a ridge	0.3
		High: Density of IAP >75% AND mature IAP stands AND situated on a steep slope, bottom of a slope or in a valley AND adjacent to points of fire ignition	0.63
Size class of IAPs	0.07	Adult: Stem diameter >5 cm, Height >1 m; includes mixed stands	0.1
		Young: Stem diameter 1–5 cm, Height 40 cm–1 m	0.64
		Seedling: Stem diameter <1 cm, Height <40 cm	0.26
Last clearing operation	0.04	No treatment	0.05
		Initial	0.3
		Follow-up (1st, 2nd, 3rd or 4th)	0.55
		Maintenance (5th follow-up)	0.1

Values associated with each factor indicate its importance (0–1) within the stand attribute category. For example, the factor relating to density of IAPs has an importance of 0.18 compared to the rest of the factors within the stand-attributes category, and the sub-factor “<1% cover” an importance of 0.41 within this factor. Invasive alien plant density sub-factors were adjusted to correspond with the density categories used by the City of Cape Town. Individual weightings of main and sub-factors were adjusted to add up to one, while retaining the original rankings of the stand attribute factors from Roura-Pascual et al. (2009)

mixed stands, i.e. when seedlings, young and mature plants are present in a MU, the ‘adult’ size class is adopted.

The timing of previous control interventions also influenced the prioritization of MUs for control in the upcoming financial year. MUs where follow-up treatments (see Box 1) have been conducted and where control interventions are scheduled for the next 12 months were given the highest priority for management. MUs where initial control of IAPs has taken place were given the second highest priority, whereas MUs that are currently at “maintenance-level” (which is the coordinated and consistent management of IAPs to maintain the plant population at low levels) were given the second lowest priority (Table 3). MUs where no control of IAPs has taken place were given the lowest management priority.

After defining each of the stand-attribute factors, the individual weightings of main and sub-factors were adjusted to add up to one. During this process, care was taken to retain the original ranking of the stand-attribute factors. Using ArcGIS 10.3, a map of each site was produced showing areas of high, medium and low priority MUs.

Results

Strategic Prioritization

The strategic goal identified by the stakeholders was to maximise effective use of available resources to control

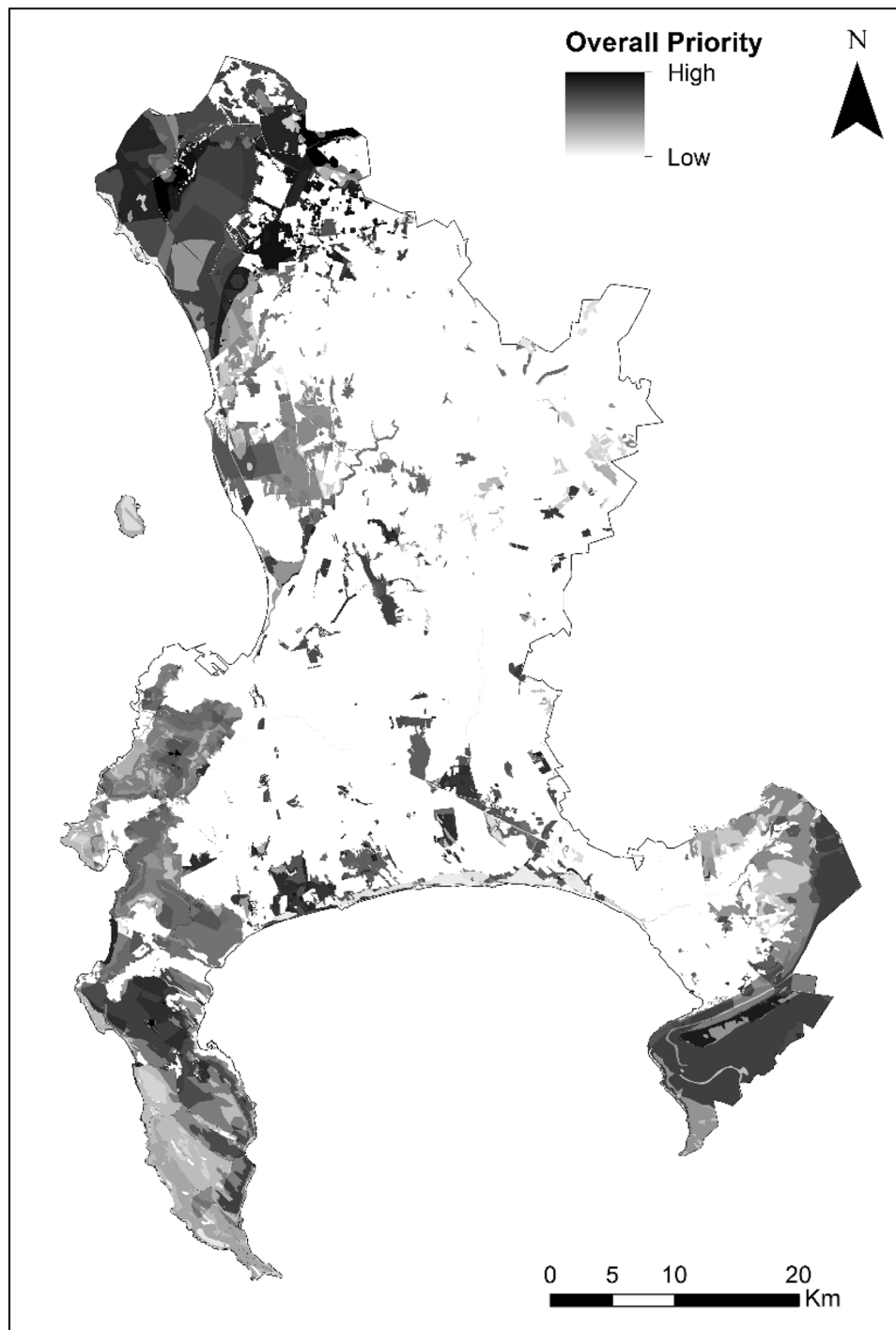


Fig. 3 Overall priority areas for the management of invasive alien plants across the City of Cape Town, South Africa. Priority areas were determined using a multi-criteria approach in which criteria were identified, weighted and assigned spatial data layers - each criterion and sub-criterion are assigned spatial data layers best representing each criterion

IAPs to achieve optimal protection of biodiversity and provision of ES. To achieve this goal, the participants identified three criteria (divided hierarchically into nine sub-criteria, Fig. 2). The most important criterion influencing the selection of invaded areas for management within the CoCT was safety and security (52%). The next level of priority

was given to areas that are important for biodiversity conservation (36%). Areas important for the provision of ES received the lowest weighting (12%).

Issues relating to safety and security were evaluated at four levels. The most important of these was the fire risk to infrastructure; areas containing high plant biomass (mainly

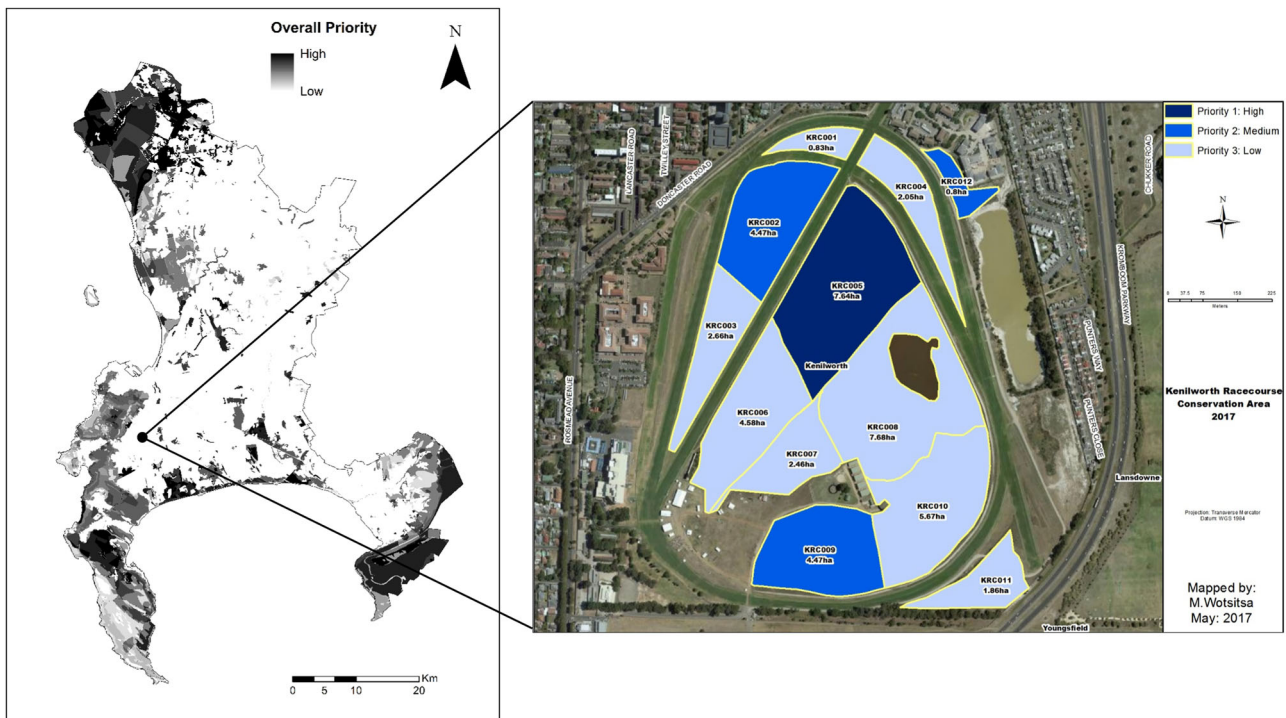


Fig. 4 A tactical (site-level) map of priorities for invasive alien plant management in the Kenilworth Racecourse Conservation Area showing areas of high, medium and low priority management units. Priority was determined based on a framework presented by Roura-Pascual et al. (2009) in which key factors involved in prioritizing areas for management were identified and assigned weights. Sites were divided into Management Units and, using information on stand attributes, were weighted accordingly and assigned priorities

woody shrubs and trees) close to infrastructure received highest priority (48%). Areas at risk of being illegally occupied were given a relatively high priority (31%) as such sites represent security threats. Proximity of areas to settlements and areas at risk of flooding received relatively low priorities (13 and 9% respectively).

Biodiversity was evaluated at two levels. The most important of these was the protected status of CBAs (67%), which were identified as part of the original BioNet analysis. These areas represent the minimum amount of terrestrial and freshwater habitat required to meet the CoCT's biodiversity conservation targets (including protected areas). Ecosystem status of remaining vegetation remnants (critically endangered, endangered, vulnerable or protected ecosystems) received a lower weighting (33%). This also included stewardship sites (see Box 1).

Ecosystem services were evaluated at three levels, with "water" receiving the highest weighting (88%). This broad category was further evaluated at two levels, the most important of which was water provisioning (75%) followed by water quality (25%). The two other criteria (coastal protection, and social aspects such as education, heritage and tourism) were identified, but each was given a weight of <10%, and thus contributed relatively little to the outcome of the prioritisation exercise.

Model Outputs

A final map was developed to show overall priority areas for IAP management across the CoCT (Fig. 3). By implementing the AHP in a GIS, output was generated as a raster layer with a value in each cell representing management priority. Areas identified as highest management priority are difficult to detect on the priority map that was produced as they are relatively small. These areas are densely invaded sites close to urban settlements and are important for biodiversity and the provisioning of ES.

Other high-priority management areas were clustered primarily in the north-western part of the city (Fig. 3). This area has several informal settlements and much of the land is densely invaded with woody alien species (especially *Acacia saligna* (Labill.) Wendl.; family Fabaceae). Consequently, this area represents a significant fire risk as well as a safety and security risk. It also contains some of the last relatively intact and ecologically functional remnants of critically endangered and poorly protected (at ca. 2%) Atlantis Sand Fynbos, as well as the endangered Cape Flats Dune Strandveld habitat. Lower-priority management sites were broadly distributed throughout the CoCT and were typically vacant, transformed land of low biodiversity and ES value situated far from urban settlements.

Table 4 Sub-factor details for each management unit of Kenilworth Racecourse Conservation Area

Management unit	Area burned in the last 12 months	Density of IAPs (% cover)	Spread based on topography	Area at fire risk (stand age, position, fire frequency)	Size class of IAPs	Last clearing operation	Total weighting	Management priority
KRC001	0.04	0.0162	0.0126	0.0091	0.0070	0004	0089	Low
KRC002	0.04	0.0162	0.0126	0.0091	0.0448	0004	0127	Medium
KRC003	0.04	0.0162	0.0126	0.0091	0.0070	0004	0089	Low
KRC004	0.04	0.0234	0.0126	0.0091	0.0070	0004	0096	Low
KRC005	0.36	0.0162	0.0126	0.0091	0.0070	0004	0409	High
KRC006	0.04	0.0162	0.0126	0.0091	0.0070	0004	0089	Low
KRC007	0.04	0.0234	0.0126	0.0091	0.0070	0004	0096	Low
KRC008	0.04	0.0162	0.0126	0.0091	0.0070	0004	0089	Low
KRC009	0.04	0.0162	0.0126	0.0091	0.0448	0004	0127	Medium
KRC010	0.04	0.0234	0.0126	0.0091	0.0070	0004	0096	Low
KRC011	0.04	0.0162	0.0126	0.0091	0.0070	0004	0089	Low
KRC012	0.04	0.0108	0.0126	0.0390	0.0448	0004	0151	Medium

The total weightings of all management units were compared and assigned high, medium and low priorities. Total weighting scores of 0.2 and above correspond with the highest management priority, whereas scores between 0.13 and 0.2 correspond to a medium priority. The lowest management priority was given to management units with a total score below 0.13

Tactical Prioritization

According to the weightings provided by Roura-Pascual et al. (2009), the most important factor influencing the selection of invaded areas for management within a specific region is the post-fire window of opportunity to remove IAPs when plants are relatively easy to remove and before they produce seeds (Table 3). Moreover, priority is given to parts of the landscape with low-density coverage of IAPs (<25% cover)—to prevent densification associated with fires—and to areas where the potential for spread into neighbouring areas is high. Additionally, areas with a high fire risk (based on stand age, position in the landscape, and fire frequency) are also prioritized for clearing (Table 3).

Case study: Kenilworth Racecourse Conservation Area

We applied this tactical prioritization scheme to identify priority MUs using the KRCA as a case study (Fig. 4). Of the 12 recognized MUs, eight were scored as ‘low’ priority for management, three as ‘medium’ priority and one as ‘high’ priority (Table 4). The ‘high priority’ MUs burned within the last 12 months and therefore require urgent management to remove IAPs before they mature and to prevent densification and spread of IAPs.

Discussion

Various approaches have been developed in the last decade to guide the prioritization of IAPs in complex landscapes (e.g. Forsyth et al. 2012; Hohmann et al. 2013; Nielsen and Fei 2015). This study builds on these methods and

introduces novel ways of approaching IAP management at a landscape and local scale. We provide a framework for spatially prioritizing IAP management across a complex and challenging urban landscape. Our strategic prioritization framework shifts the management focus away from ad hoc approaches and provides guidance on where best to focus IAP management efforts across an urban landscape (Fig. 5). Furthermore, by modifying and applying an existing IAP management framework in an urban setting, we also provided tactical guidance for on-the-ground IAP control operations at the site level (Fig. 6). The formalized prioritization approach for IAP management we have applied here is collaborative, defensible, reproducible, spatially explicit, systematic, and transparent. Such advantages are particularly desirable when multiple management objectives add to the complexity of urban planning.

While the CoCT presents a useful system to explore the unique challenges associated with managing urban plant invasions in South Africa, our dual prioritization approach can be tailored to address different IAP management objectives specific to other urban centres around the world.

Safety and Security

Safety and security was the most important factor influencing the selection of invaded areas for management within the CoCT (Fig. 2). The most important sub-criteria were ‘fire risk to infrastructure’ and ‘risk of land invasion’.

Fire risk to infrastructure

Fire is an important process in fynbos, which is both fire-adapted and fire-dependent (van Wilgen 2009) and managing fynbos equates to managing fire. Fire has a

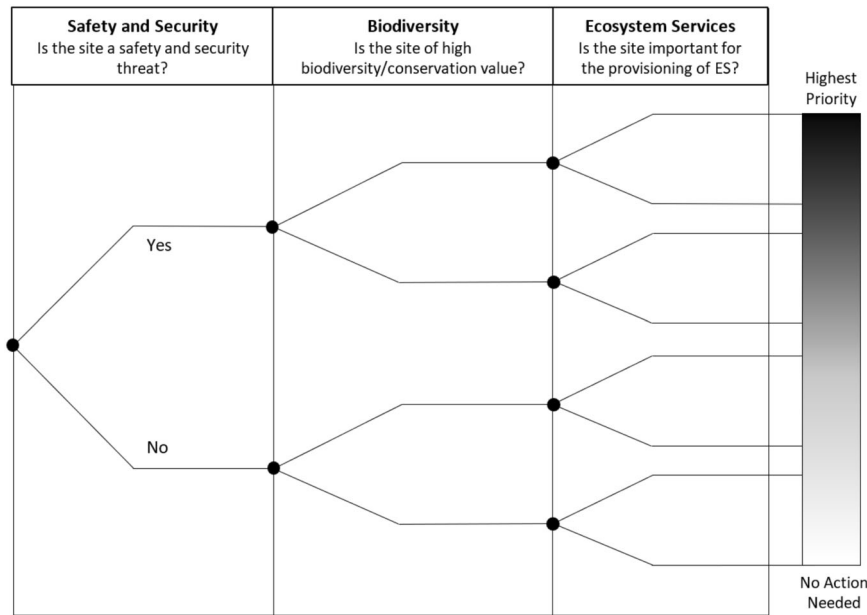


Fig. 5 Decision framework for strategic prioritization of areas for the management of invasive alien plants in urban areas

considerable influence on decision-making in the city and remains a critical component of integrated invasive plant management (van Wilgen et al. 1994); managers often reprioritise clearing operations and reallocate funding in response to fires (Roura-Pascual et al. 2009). Fragmentation associated with urban development interrupts the natural fire regime (Regan et al. 2010), and maintaining this essential process is a major challenge within the urban matrix.

Many residential properties along the urban edge within the CoCT border fynbos vegetation (Alston and Richardson, 2006). Many of these properties are regular sources of alien plant propagules, which disperse, establish and spread into the natural vegetation, posing a risk to biodiversity (see also McLean et al. (2017) for discussion of the role of urban gardens as launch sites for plant invasions in the Western Cape). The increase in biomass resulting from alien plant invasions close to urban infrastructure represents a substantial fire risk (Fig. 1b) (van Wilgen et al. 2012) - accidental (and often intentional) fires started by people may lead to overly frequent and uncontrolled fires, which can threaten property and the safety of people (van Wilgen and Scott 2001). Other areas such as vacant properties, public open spaces and riparian areas also become invaded to the degree that they pose a fire risk to infrastructure. Cape Town is currently experiencing one of the worst droughts in recent history. Drought and fire contribute to the spread of IAPs, which in turn can worsen the effects of drought and fire (Littell et al. 2016). This results in a feedback loop where stress from increased drought and fire severity leads

to increases in plant invasions, which places further pressure on biodiversity and ES.

Management of the fire-adapted and fire-prone fynbos often results in conflict due to the need for prescribed burning to achieve ecological goals versus the prevention and suppression of wildfires for the safety of humans - public safety becomes the primary goal and not biodiversity conservation (van Wilgen et al. 2012). This requires integration of both ecological and societal aspects in the development of an adaptive fire management plan.

Risk of land invasion and criminal activity

Some communities in Cape Town view vegetation remnants as unsafe places characterised by criminal activities (CoCT 2008). This is largely because the sites are covered in thickets of IAPs (especially Australian acacias) and receive little to no management (CoCT 2008). For example, in poorer suburbs, open spaces invaded by Australian acacias are associated with crime and are referred to colloquially as the ‘bush of evil’ (Rebello et al. 2011; Allsopp et al. 2014). The dense alien vegetation, which grows taller than the indigenous vegetation, screens illegal activities and may provide shelter for vagrants. As a result, these areas are often points of ignition for fires, which are difficult to control due to the high levels of alien plant biomass. Problems of this nature in the CoCT have led to vegetation clearing efforts with the purpose of preventing crime, often in response to outcries from nearby communities. For example, land earmarked for future housing developments

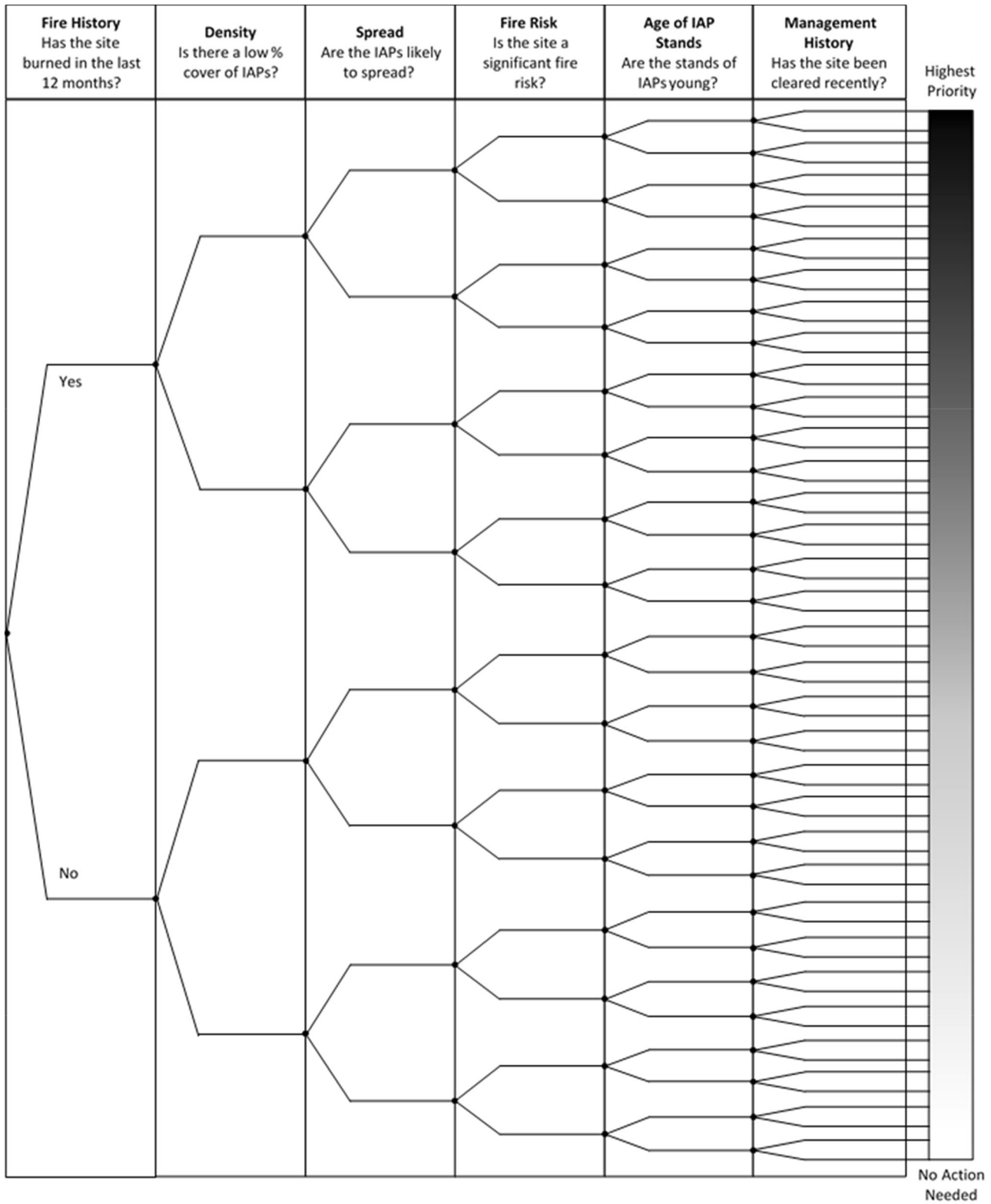


Fig. 6 Decision framework for tactical prioritization of Management Units for on-the-ground control operations of invasive alien plants in urban areas

are often high-risk areas for land invasion, criminal activities and fires and the responsible department will control dense stands of IAPs to satisfy their primary objective, which is to improve public safety. Follow up control, however, is seldom scheduled until the IAPs reach maturity and the stands are once again densely invaded. Coordination of IAP control across the city has, to date, been ad hoc and is only initiated when sources of funding become available. Thus, when crime levels increase in a particular area, local communities request removal of alien vegetation, and only then is funding released. Such programmes generally do not result in sustainable, nor effective IAP control. This approach has, however, started to change as departments begin to realise the value of clearing and maintaining invaded sites, which often results in cost-saving and reduction in public complaints.

Managing urban plant invasions is largely a social necessity, because controlling IAPs and maintaining the appropriate fire regime for the indigenous vegetation will maintain it in a state that is less attractive to criminals and less threatening to local communities. Improving public safety is an effective means of motivating for the conservation of poorly managed or unmanaged sites. The challenge is to manage these sites in such a way to restore biodiversity and ES provision, while improving public safety.

Urban Ecosystem Services

While the science of ES is advancing rapidly (Guerry et al. 2015), knowledge of how decision-makers and decision-making processes at different levels apply such notions in planning is poor. Although there has been widespread adoption of ES-based frameworks in policy and practice, both ethical and operational challenges related to using ES as the foundation for management remain, particularly in the developing country context (Sitas et al. 2016). This necessitates a better understanding of the ES concept, particularly as it relates to the planning and implementation of strategies aimed at promoting human well-being. Funk et al. (2013) argue that managers must make a broader case for investing in the control of invasive species to prevent the loss of ES.

Despite the use of some IAPs to provide ES, there is a general lack of understanding of how to predict and manage, or even measure the effects of IAPs on ES (Eviner et al. 2012). This can limit the decision-making ability of conservation managers. In the case of our study, ‘ecosystem services’ received the lowest weighting of all three criteria identified in the workshop (12.43%). While this may be an accurate depiction of stakeholder views, we argue that, given the importance of ES in enhancing

human well-being and the role IAPs have in the provisioning of such services (including associated conflicts of interest; Potgieter et al. 2018), the complexities associated with ES (particularly in an urban environment) may have been poorly understood and consequently underrepresented in the decision model. An additional factor which may explain the low weighting given to ES is that water provision (a vital ES obtained mainly from surface water from catchment areas) occurs mostly outside the city’s boundaries; of the six dams supplying water to the city, only two are managed by the CoCT as the catchments are managed by the provincial governmental organisation. IAPs have, however, become a dominant feature in the catchments that supply Cape Town with water. Vegetation dominated by IAPs uses significantly more water than native vegetation without IAPs, reducing surface run-off and compromising the supply of water to the city (Le Maitre et al. 2011). These effects are exacerbated by the current drought conditions in the city.

Resource Allocation

The outcome of our strategic prioritization suggests that an alternative approach to secure consistent levels of funding for IAP control in an urban environment may be to motivate for improving public safety and security rather than conserving biodiversity; biodiversity is not well understood and often not highly valued as an asset by urban decision and policy makers.

Timely intervention to control the spread of IAPs can minimize economic and ecological damages, whereas lapses or delays in funding control efforts can be extremely costly in the long run (Funk et al. 2013). Consistent funding levels allow for more effective invasive species control, however, many barriers affect the allocation of resources to IAP management (Table 1). Allocating funding for managing IAPs is challenging, because of competing priorities and the absence of a long-term strategy. Environment-related matters in South Africa fall within both national and provincial levels of legislative competence, and consequently local government prioritizes development and service delivery over environmental aspects, such as invasive species control (Ruwanza and Shackleton 2016). Invasive species management is not independently funded, but is mostly reliant on available, short-term operational funding from the different departments responsible for managing land parcels within the CoCT (Irlich et al. 2017). Furthermore, operational funds and access to funding fluctuates widely between financial years, which complicates planning efforts. Existing planning frameworks for the CoCT do not provide adequate tools for prioritizing IAP management

(e.g., Integrated Development Plan, IDP; Spatial Development Framework, SDF), which consequently hinders implementation and obstructs potential budget allocation (Irlich et al. 2017). Thus, IAP planning frameworks should rather inform such agendas.

Tactical Control Operations

In addition to funding constraints, managers in urban areas encounter numerous challenges that may affect IAP control operations on the ground, many of which are particularly prevalent in developing countries. Many of the factors identified in our tactical prioritization approach may be influenced by the complex mechanisms associated with urban areas.

Unlike most other ecosystems, urban environments have exceedingly large numbers of land managers present (e.g., privately-owned property, national and provincial government land, municipal property managed by different departments). This can make coordination of management activities extremely difficult (Gaston et al. 2013). A greater number of landowners also means a greater likelihood that different landowners will have different incentives, policies, or practices for managing invasive plants. For example, road verges (which are particularly susceptible to plant invasions; von der Lippe and Kowarik 2008) in CoCT are managed by the Recreation and Parks Department who have different, and often conflicting management objectives, to that of IAP managers. These different departments may carry out IAP control operations to achieve these alternate objectives (e.g., to improve public safety), however, such management decisions are seldom made in coordination with specialist IAP managers, resulting in ineffective IAP control. For example, initial clearing operations may achieve the desired goal in the short-term, but follow-ups are often neglected (due to funding uncertainties or other constraints) or are no longer seen as a priority. Only once the alien plants have re-established, does the area become a priority again.

Accessibility also presents a considerable challenge in controlling alien plant invasions in the urban landscape. Various parcels of land fall under different management authorities and accessing these properties can be challenging. For example, a private property may be identified as a high priority for management, but the owner may not be contactable or alternatively may forbid access to the property.

The safety and security of IAP control teams themselves is often at-risk due to criminal activity at sites on which they work, and there have been several cases of team members being robbed at gun point. Tension may also result from sites being cleared of IAPs without considering the social ties associated with the target species (Dickie et al. 2014).

Limitations

A limitation to this approach is that results are only as good as the quality of data, which is particularly important for criteria with highest weights (Forsyth 2013). The composition of the workshop participants is important for reaching consensus since individuals within the group could have opposing priorities or may be unwilling to deliberate and potentially change their views on contentious issues, thereby making it impossible to reach unanimous decisions. Including stakeholders from diverse disciplines (e.g., government representatives, social scientists, and members of the public) in such workshops potentially strengthens the decision model, allowing for more defensible outcomes.

Conclusions

Experience has shown that successful IAP management requires well established priorities, clear time-based goals, adequate resources to achieve the desired level of control, and support from multiple stakeholders (e.g., Januchowski-Hartley et al. 2011; Forsyth et al. 2012; Hohmann et al. 2013). Efficient management of IAPs in urban landscapes is especially complicated, because of the multiple interacting environmental and socio-economic factors. IAP managers in urban areas across all geographic regions need to overcome the barriers characteristic of urban areas to effectively manage urban plant invasions and ensure the continued provision of ES that are essential for human well-being.

Our application of the AHP used available data, expert opinion, and science-based heuristics to inform the prioritization of IAP management. It can, however, also be expanded to incorporate new insights provided by additional data, more stakeholders, or new models of relevant system processes. The weights and rankings can have application in areas with similar ecological and socio-economical characteristics (De Lange et al. 2012), but the approach applied in this study should be useful in all urban settings to guide the selection and prioritization of areas for IAP management. As new data become available and as levels of understanding of the dynamics of plant invasion improve, rankings and weights can be adjusted, and criteria can be added or removed.

The process followed here has established a set of clear, transparent and agreed priorities which can be used to guide the allocation of available funds. The overall approach used to prioritize areas for IAP management resulted in an intuitive framework for dealing with the complexities involved in decision-making processes in urban environments. It also offers managers and scientists the opportunity to share experiences and knowledge on best-management practices for controlling IAPs in a quantifiable and

transparent way, while simultaneously identifying barriers that hinder the effectiveness of IAP management operations.

Applying the AHP within a GIS allowed us to generate a spatial prioritization of IAP management across a complex urban landscape. Modifying an existing IAP management framework and applying it to an urban landscape proved useful in guiding tactical management actions at the site level.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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