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An assessment of the evolution, costs and effectiveness of alien plant control operations in Kruger National Park, South Africa

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Abstract

Alien plants were first recorded in 1937 in the 2 million ha Kruger National Park (KNP, a savanna protected area in South Africa), and attempts to control them began in the mid-1950s. The invasive alien plant control program expanded substantially in the late 1990s, but its overall efficacy has not been determined. We present an assessment of invasive alien plant control operations over several decades in KNP. We based our assessment on available information from a range of control programs funded from various sources, including national public works programs, KNP operational funds, and foreign donor funds. Over ZAR 350 million (~ US$ 27 million) has been spent on control interventions between 1997 and 2016. We found evidence of good progress with the control of several species, notably *Opuntia stricta*, *Sesbania punicea*, *Lantana camara* and several aquatic weeds, often because of effective biological control. On the other hand, we found that over one third (40%) of the funding was spent on species that have subsequently been recognised as being of lower priority, most of which were alien annual weeds. The allocation of funds to non-priority species was sometimes driven by the need to meet additional objectives (such as employment creation), or by perceptions about relative impact in the absence of documented evidence. We also found that management goals were limited to inputs (funds disbursed, employment created, and area treated) rather than to ecological outcomes, and progress was consequently not adequately monitored. At a species level, four out of 36 species were considered to be under complete control, and a further five were under substantial control. Attempts to control five annual species were all considered to be ineffective.

On the basis of our findings, we recommend that more studies be done to determine impacts associated with individual invasive alien species; that the criteria used to prioritise invasive alien species be documented based on such assessments, so that management can justify a focus on priority species; and that funding be re-directed to those species that clearly pose greater threats, and for which other solutions (such as biological control) are not an option.

Keywords
Biological control, invasion, protected area, savanna, Working for Water

Introduction

The mitigation of threats to biodiversity is a principal aim of protected area management worldwide. Large sums of money are spent to address these threats (van Wilgen et al. 2016), which include urban and agricultural encroachment, invasive species and pollution (Salafsky et al. 2008). However, it is also widely acknowledged that funds for conservation are scarce and cannot meet all demands everywhere (Murdoch et al. 2011). If limited funds are to be spent wisely, an initial plan and periodic assessments of management effectiveness are essential (Leverington et al. 2010, Legge 2015, van Wilgen et al. 2016). These assessments are needed to establish whether management interventions are achieving the desired outcomes, and if not, whether or how management could be adapted to become more effective (Foxcroft and Freitag-Ronaldson 2007). Evaluations are also needed to establish whether the outcomes of management are meeting the expectations of long-term investment of public and private resources (Legge 2015).

Millions of dollars have been devoted to the management of invasive alien plants across the globe, including in protected areas, and robust assessments are needed to establish whether the objectives of management are being met. Several accounts of the ecology of alien plant invasions and the philosophy and history of their management in protected areas have been published (e.g. McKinney 2002, Pauchard et al. 2004, Foxcroft and Freitag-Ronaldson 2007, Foxcroft and Downey 2008, Foxcroft et al. 2013). However, there have only been a few quantitative accounts of the costs and effectiveness of management interventions (see McConnachie et al. 2012, Fill et al. 2016, van Wilgen et al. 2016 for some examples). This is often because researchers and managers operate in different environments, with different goals, different performance measures, and different funding streams. This makes large-scale assessments difficult, because available information from one environment is often not adequate for, or relevant to the other. The lack of invasive alien control program assessments is typical of many, if not most, protected areas globally (Naidoo et al. 2006, Wilson et al. 2007). In a review of invasive alien plant control research, Kettenring and Adams (2011) found that very few studies had evaluated the costs of invasive species control, and these authors urged researchers to provide more complete evaluations of the costs and effectiveness of control interventions.

The benefit of assessments lies primarily in their utility for informing the optimization of control approaches and procedures. Thus, assessments should evaluate not only the cost-effectiveness of programs in terms of money spent on alien species and the ecological outcomes, but also those aspects of the program goals, planning and implementation processes that influenced where and how money was allocated. Assessments should also note which species were prioritized for control, why they were targeted, whether management goals are being met and the constraints that may be limiting current approaches. Budget constraints that influence the choice of control options should also be noted, and the management goals which should guide control programs should be interpreted (Epanchin-Niell and Hastings 2010). Despite decades of expenditure in some countries, assessments have largely been limited to documenting annual control costs (e.g. Pimentel et al. 2005, Sinden et al. 2005); reviews of specific approaches (e.g. biological control, Palmer et al. 2010); or had a focus on specific species (e.g. Bonesi and Palazon 2007, Hazelton et al. 2014, Lindenmayer et al. 2015, Dew et al. 2017). For example, Thorp and Lynch (2000) describe how the weeds of national significance were determined for Australia's control program, and Nel et al. (2004) describe species prioritization for South Africa's Working for Water program. Such information should be considered when evaluating how money was allocated to the control of particular species. Assessments of conservation programs have demonstrated how explicit consideration of goals and objectives can help recommendations for improving these programs. For instance, Parr et al. (2009) considered the management framework, including goals and objectives, of biodiversity conservation programs in Kakadu National Park (Australia) and Kruger National Park (South Africa), generally. Their approach was instructive in demonstrating how explicit consideration of management provided insight into the current status and outcomes of biodiversity conservation efforts in these parks.

In this paper we assess the evolution, costs and effectiveness of alien plant control operations in Kruger National Park (KNP), South Africa. The KNP provides an example of a concerted effort to control invasive alien plants over a very large area, and over several decades. The objectives of this study were to 1) document the goals of alien plant management and the plans for achieving them; 2) identify the species targeted for control and the historical costs of their management; 3) document and assess the effectiveness of the management interventions in reducing the abundance or spread rates of the species; and 4) make recommendations for improving the control efforts.

Methods

Study area

The KNP (~2 million ha) became a protected area in 1898, and gained national park status in 1926. It is situated in the northeastern corner of South Africa, along the border with Mozambique. The mean annual rainfall varies between 350 mm in the north and 750 mm in the south. The vegetation is a well-wooded savanna, and seven major river systems traverse the park from west to east. The KNP is one of few protected areas in South Africa in which invasive alien species, particularly plants, have been managed for more than fifty years (Foxcroft and Freitag-Ronaldson 2007, Foxcroft et al. 2008, Foxcroft et al. 2013). Early in the park's history, the intentional planting of ornamental plant species in tourist camps and staff village gardens was the primary source of the majority of alien plant species introductions (Foxcroft et al. 2008). Increasing urbanization and development outside of the boundaries of KNP subsequently facilitated further plant invasion, especially along rivers (Foxcroft et al. 2008), so that the riparian zones became the most severely invaded habitats (Foxcroft and Richardson 2003). Non-riparian areas also became invaded by alien plant species that were dispersed by birds and mammals, or by human use of roads, tourist camps, and gardens (Foxcroft and Richardson 2003, Foxcroft et al. 2008). In 1997, invasive alien plant control operations were substantially expanded as a result of inflows of funding that followed the establishment of a democratically-elected government in 1994 (van Wilgen and Wannenburgh 2016).

General approach to this assessment

Our assessment was based on information and data from a range of sources. The control of invasive alien species in KNP has relied on several different funding streams, including KNP's own sources for ecosystem management, government-sponsored public works programmes, and foreign donor funding. Each of these sources differed with regard to the goals to be achieved, the formats for data storage, and the requirements for progress reporting. Information on invasive alien plant control operations in KNP has generally been recorded for areas where the control teams worked, and these records include the species that were subjected to control, and the costs of control. However, the data were not always recorded consistently or clearly. For example, the boundaries of spatial units on which control teams worked were changed over time, or in some instances only a portion of the spatial unit on record was treated. In other cases, teams worked on alien plant control as well as on other activities, and the costs of each activity were not recorded separately. Some interventions were recorded as having targeted a certain species, whereas in reality several species were treated in the same operation. For these reasons it was often necessary to make assumptions about the distribution of costs, or species targeted, and we were consequently only able to make a broad-scale assessment of control interventions and their effectiveness. Where assumptions were made, these are stated in the descriptions of methods below. Nonetheless, we believe that reporting the outcome of this assessment in the scientific literature is warranted, given the scarcity of such accounts and their importance in terms of addressing the gaps between research, implementation and monitoring the efficiency and cost-effectiveness of control.

Planning and monitoring

Planning and monitoring are essential elements of management, and clear goals and regular assessments of outcomes are necessary to guide interventions and to gauge progress. We reviewed the systems of planning, management and the monitoring of outcomes based on KNP's management plans and protocols, and on published sources describing the development of management philosophy and its implementation (see, for example, Biggs and Rogers 2003, Foxcroft 2004, van Wilgen and Biggs 2011).

Control measures and effectiveness of control

The prioritization of invasive alien plant species, and their assignment to management intervention categories, has been a fairly recent development in KNP. The initial priorities were only determined in 2008, using a multi-criteria decision-support method that prioritized invasive alien plant species in South Africa's savanna biome (Forsyth and Le Maitre 2011). The criteria for prioritizing species included their impact on biodiversity, on ecosystem services, their relative ease of control, and dispersal potential. An original list of 136 species was reduced in 2015 to 28 species, and ranked by KNP-based ecologists and managers according to the level of concern to KNP (species were divided into those of higher and lesser concern, with a separate category for new incursions with scattered populations that should be prevented from spreading; Table 1). We used this classification as a basis for examining the allocation of funding to invasive alien plant control projects. We also reviewed the protocols and methods that were used to control invasive alien plant species in KNP over the past two decades. These protocols or measures were of two broad types: species-based control, and area-based control. Control measures that targeted particular species included (1) management of species with scattered populations; (2) integrated control of aquatic weeds (*Eichhornia crassipes*, *Pistia stratiotes* and *Salvinia molesta*); and (3) biological control of selected species. Control measures that targeted particular areas entailed labour-intensive piece work on contract for either (4) perennial plants or (5) annual plants. In our analysis, we considered these five approaches separately (annual and perennial plants were considered separately to be able to illustrate the amounts spent on each category, Table 2). The overall effectiveness of control on individual species was assessed, based on the experience of the authors, as follows: (1) unknown (insufficient information to determine effectiveness at this stage); (2) ineffective (control measures are having no discernible effect on the species concerned); (3) moderately effective (spread rates are slowed, but not reversed); (4) substantial (spread rates are reversed, and populations are decreasing); and (5) complete (the threat of the species has been eliminated, and no further action is required; this would apply, for example, if a species were eradicated, or where effective biological control alone prevents re-establishment and spread).

Table 1. Priorities assigned to invasive alien plant species in the Kruger National Park.

Priority	Description	Management approach
Species of higher concern for which separate, dedicated control plans should be developed	Species identified as of sufficient importance to justify a species-specific management plan	Species-dependent. Plans are in development for *Parthenium hysterophorus* (aligned with the national-level approach to this species, outlined by Terblanche et al. 2016), *Chromolaena odorata*, *Opuntia stricta*, and aquatic weeds.
Species of higher concern targeted for control through ongoing clearing and follow-up treatments	Species that have established significant invasive populations in KNP.	Control normally involves labour-intensive mechanical clearing conducted by teams funded by public works programmes.
Incursions with scattered populations (either new species, or isolated outbreaks of species with established populations elsewhere in KNP)	Species targeted as a result of them exceeding a threshold (being noted as a new occurrence, and hence requiring immediate attention to prevent further spread).	Targeted clearing at sites where the species occurs at low densities. Control normally executed by teams funded by KNP Conservation Management operational funds.
Species of lower concern	Invasive alien plant species not considered to be a priority for management	Species that should not normally be targeted for control unless they co-occur with priority species.

Costs of control

The cost of invasive alien plant control was assessed for the period 1997–2016, as there were no reliable records for prior periods. We obtained the annual total amounts allocated each year to alien plant control in KNP from various funding sources. Alien plant control interventions associated with public works funding were contracted out to teams at an agreed cost based on the area that required control, the species present, and their cover (see Neethling and Shuttleworth 2013). The public works programs had recorded the costs of contracts in a spatial database that covered the period 2002 onwards to present. The records included the species that were treated, the density of the invasions, the cost of the operation, the number of people employed, and whether the intervention was an initial clearing, or a follow-up to remove emergent seedlings or re-sprouts. We extracted the data on annual costs per alien species from this database. We used these data to determine the proportion of total funds spent on each species between 2002 to present. Public works programmes were initiated in 1997, but detailed records of the distribution of funds were only available from 2002 onwards. In order to estimate the expenditure per species for 1997–2001, we assumed that the annual funds for those years were spent on individual species in the same proportion as from 2002. In an attempt to prevent cleared areas from becoming re-invaded from outside of KNP, teams also operated on land beyond the park boundary (Fig. 1). Due to recent budget cuts and an emphasis on neighbouring private land, these operations have been limited to 1.5 km from the park boundary, but up to 10 km for some streams and perennial rivers that flow into the park. We separated the control costs incurred inside and outside of KNP.

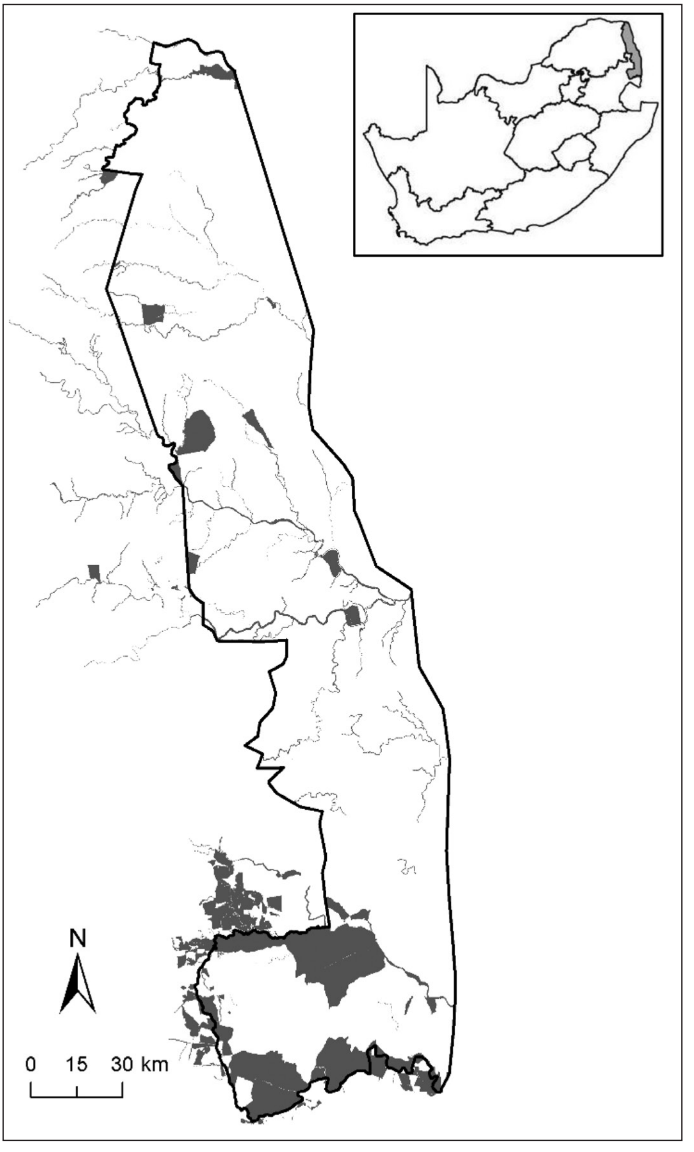

Figure 1. Areas in which alien plant control operations were carried out inside and outside Kruger National Park, South Africa (2002-present). This illustrates the extent of preventative clearing intended to reduce the risk of ongoing invasion from outside of the protected area. The black line delineates the park boundary. Inset shows the location of Kruger National Park within South Africa.

The amounts allocated to alien plant control contracts over the study period accounted for about 60% of the total funds spent. The remaining funds were used for overhead expenses, which included herbicides, training, equipment, supervision, administration and the establishment and operation of mass-rearing facilities for biological control agents. We accounted for overheads by increasing the recorded costs

Table 2. Funding for alien plant management in the Kruger National Park. Funding sources and costs (1997–2016) are associated with five management intervention categories aimed at the control of alien plants in the Kruger National Park.

Management intervention category	Funding source	Description	Duration	Cost (millions of 2016-equivalent ZAR)
Species-based intervention: Management of species with scattered populations	KNP management budget	Mobile team of workers employed by KNP to target isolated populations of invasive alien plants	1982–present	31.4
Species-based intervention: Integrated control of aquatic weeds	Mpumalanga Province	Application of aerial spraying of selected water bodies	2002–present	14.0
Species-based intervention: Biological control of certain species	Public works programs	Targeted programs aimed at the control of selected species	1985–present	Overhead cost, not accounted for in records
Area-based intervention: Labour-intensive piece work to clear perennial invasive alien plants on contract	Public works programs	Contract-based piece work, with the aim of creating employment as well as reducing the spread and extent of invasive alien plants (van Wilgen and Wannenburgh 2016)	1997–present	180.8
Area-based intervention: Labour-intensive clearing by workers employed full-time	Donor funding (Royal Netherlands Government)	Foreign donor funds were used to supplement Public Works funds, with the same goals as for public works programmes	1997–1999	8.3
Area-based intervention: Labour-intensive piece work to clear annual weeds on contract	Public works programs	Contract-based piece work (often with the aim of creating employment).	1997–present	105.6

for each species by a percentage that would bring the total costs for each year up to the full amount spent in that year. To account for inflation, we used the annual consumer price index to inflate all monetary values to 2016 South African Rands (ZAR; 1 US$ ~ ZAR13.5).

Results

Planning and monitoring

The compilation of a management plan is a legislative requirement in South Africa for all protected areas (National Environmental Management: Protected Areas Act, Act 57 of 2003). The KNP management plan (Freitag-Ronaldson and Venter 2009) addressed several themes, one of which was the threats posed by invasive alien species. The KNP's objective with respect to alien species management was "to anticipate, prevent entry and where possible control invasive alien species, in an effort to minimise the impact on, and maintain the integrity of indigenous biodiversity" (Freitag-Ronaldson and Venter 2009: 32). This high-level objective was taken further in separate "management-unit clearing plans" (MUCPs) that provided details of where, and on which species, to focus the funds available for management for a five-year cycle (Foxcroft and McGeoch 2011). At the next level, annual plans of operation were drawn up each year, detailing the allocation of available funds to specific projects.

The KNP has also adopted an overarching philosophy of adaptive management. Under this framework, management interventions are initiated by responding to thresholds of potential concern (Biggs and Rogers 2003). These thresholds are defined for ecosystem indicators, and if a threshold is reached, then management interventions are considered; alternately, the threshold can be recalibrated (Biggs and Rogers 2003). The thresholds for invasive alien species included new occurrences, 5% increases in distribution, and increases in density. In reality, only the first threshold has been used to date due to a lack of data and monitoring (Foxcroft 2009). This system provided further guidance to managers as it identified new priorities for intervention from time to time (see appendix Table 2 in Foxcroft 2009 for examples).

In practice, however, the high-level goal in the KNP management plan has not been effectively carried forward to the 5-yr MUCPs. The MUCPs allocated funding to the control of particular species in particular areas, with goals that quantified the amounts to be spent, the number of people to be employed, and the areas to be treated. Monitoring of outcomes had a focus on these goals, and there were no goals that described the desired outcome in terms of reducing invasive alien plant invasions to manageable levels, what those manageable levels would be, and how long it would take to achieve them (Nicholas Cole, pers. comm.). In the absence of a monitoring program that is focussed on outcomes, it was not possible to objectively assess management effectiveness (see discussion).

Approaches to control

By far the largest proportion of funds was sourced from the nationally-funded public works programs, and was used to fund labour-intensive piece work on contract. The other management intervention categories also made important contributions to the overall outcomes of alien plant management in KNP. These management intervention categories are not entirely mutually exclusive; for example, biological control can make labour-intensive mechanical clearing more effective, if the two are used in tandem. The protocols used in each category are described below.

Species with scattered populations. Once an alien species has invaded an area, targeting isolated or scattered populations delivers the most effective outcomes for containing or reducing the spread of invasions (Higgins et al. 2000). A good example of how this approach has been used in KNP is provided by *Opuntia stricta*, where larger infestations within a defined management area have been managed using the biological control agents *Dactylopius opuntiae* and *Cactoblastis cactorum*, but newly-detected and isolated populations have been targeted for removal using herbicides. In addition, the adaptive management system that identifies alien plant species that have reached a threshold of potential concern constantly generates the need for management capacity to deal with these occurrences as they arise. Management of these instances requires an agile workforce that can be rapidly assigned to new occurrences as they are detected. Such agility is not possible in the case of control projects funded by public works, as contracts are awarded on an annual basis for fixed areas, and cannot be altered. Consequently, this work has been carried out by KNP's own alien biota control team who are permanently employed, and where these constraints do not apply.

Integrated control of aquatic weeds. The management of aquatic invasive alien plants is characterised, in KNP as elsewhere, by a tension between chemical control using aerial spraying and biological control. Chemical control is effective for removing dense invasions on water bodies but needs to be applied repeatedly as surviving plants reinvade the cleared area. In addition, herbicides could have adverse environmental consequences. Biological control, on the other hand, is a more sustainable and benign solution, but it takes longer to become effective, and cannot deal rapidly with large infestations or highly variable seasonal changes (e.g. annual flushing of a river by floods followed by rapid reinvasion). Hill and Coetzee (2017) observed that "while manual removal …. can be successful, it is labour-intensive. Although one of the pillars of the [public works programs] is job creation through alien plant removal, this method is really ineffective for water weeds and this work force [would be] better used on controlling terrestrial weeds in South Africa". Mechanical control of aquatic weeds in KNP is also unacceptably risky due to the presence of hippopotami and crocodiles. Chemical methods have therefore been widely used against aquatic weeds in KNP. *Eichhornia crassipes* was sprayed 2 – 3 times per year on the Letaba and Crocodile Rivers and on some dams, using resources supplied by the Mpumalanga Province. *Pistia stratiotes* and *Salvinia molesta* were additionally targeted with biological control agents, first released in 1985 and 1992, respectively. An example of the tension between chemical and biological control approaches is provided by the case of Sunset Dam, an off-channel water body that is extremely popular with tourists and also heavily invaded by *P. stratiotes* (Fig. 2). Following a decision to stop chemical control of *P. stratiotes* in 1997, the dam became completely covered by *P. stratiotes.* The biological control agent *Neohydronomus affinis* was released in 1997, resulting in the almost total elimination of *P. stratiotes* by October 1998 (MacFadyen et al. 2008). After the initial reduction, the dam reverted to full cover of *P. stratiotes* again by May 1999. This alternating cycle between invaded (complete cover) and clear (complete absence of any plants) persisted for about six years, which was considered unsatisfactory by many managers and tourists. Those responsible for the biological control program were able to resist substantial pressure for the re-introduction of chemical control for long enough, and since May 2004, the dam has remained free of *P. stratiotes* due to the persistence of the biological control agents.

Biological control. Current policy in KNP recognises the imperative to utilize biological control, given that it is relatively cheap, sustainable, and safe (van Driesche and Center 2013, van Wilgen et al. 2013). Biological control in KNP began in 1985, and has been developed in close collaboration with biological control researchers based at the Plant Protection Research Institute and the University of Cape Town. Currently, 22 biological control agents have been released on seven invasive alien plant species in KNP (Foxcroft et al. 2017). Five alien plant species are under either complete control, or the agents contribute substantially to the control thereof (the cactus *Opuntia stricta*, the woody shrub *Sesbania punicea*, and three aquatic species: *Salvinia molesta, Azolla filiculoides* and *Pistia stratiotes*). A facility to breed large numbers of biological control agents has also been established in KNP, with funding from the public works program. This facility supplies biological control agents for distribution across the KNP against several prominent invasive alien plant species (notably the agents for control of *O. stricta*).

Labour-intensive piece work to clear perennial alien plants on contract. This work was conducted by emerging entrepreneurs who were awarded contracts for "piece work". The work itself differentiated between initial clearing or follow-up clearing, to be conducted on a defined area of land and focusing on specific species. Perennial re-sprouting species were typically subjected to an initial clearing in which mature plants were cut at the base and the stumps treated with herbicide to prevent re-sprouting. Treated areas were then revisited on an annual basis to control any re-sprouting stumps with herbicides and to remove or spray emerging seedlings. The total price awarded to each contract was estimated based on the particular species and their density (Neethling and Shuttleworth 2013). The goals of this work were twofold, to control of invasive alien plants and to provide employment. In order to meet the additional goal of maximising employment, and distributing this evenly among communities from all areas adjacent to KNP, projects were distributed across the KNP, several of which may not necessarily have been in areas with concentrations of higher-priority alien plant species. In addition, as found in similar projects, the existence of dual goals resulted in differences of opinion regarding priorities for spending (van Wilgen and Wannenburgh 2016). Cleared areas were frequently revisited to conduct follow-up operations, leading to some concerns among KNP managers that certain areas were being cleared too often (we recorded up to 16 follow-ups on the same site). In addition, annual plans of operation, aligned with MUCP targets, have been inflexible, making it difficult to move the operations to new areas if this became necessary.

Clearing of annual weeds. Annual invasive alien weeds have been extensively targeted in KNP (Table 3). Annual weeds tend to invade disturbed areas in natural ecosystems, especially riparian zones or overgrazed areas (e.g. Morris et al. 2008), where, due to their wide distribution and high abundance in patches, they also provide opportunities to create employment. However, the practice of allocating funds to clearing annual weeds is arguably not always an effective use of scarce resources because annual weeds survive as seeds over the dormant season, and re-appear each year; in addition, most of them (with the notable exception of *Parthenium hysterophorus*) are not known to cause substantial negative impacts; see Discussion).

Effectiveness of control interventions

In the case of KNP, we were not able to systematically assess the effectiveness of control interventions, as these were not effectively monitored. No clear goals were set out in the 5-yr plans (MUCPs), and monitoring was limited to recording the species that were targeted, and the costs of control and follow-up. Nonetheless, there are several approaches that can be used to gauge effectiveness at a broad level. These are discussed briefly below.

Anecdotal evidence of progress: KNP staff and field rangers are generally of the opinion that mechanical and chemical control interventions have been effective in reducing the density of many species, even though there are almost no quantitative data to substantiate this impression. For example, long-serving staff can recall very dense stands of *Lantana camara* along the Sabie River, with impenetrable stands of over 2 m high (K. Maggs, W. Lotter, pers. comm), and these stands are not present today (Fig. 2). Evidence suggests that there was initially a great deal of early effort without demonstrable effect. For example, between 1996 and 1999, KNP teams employed manual labour to remove 8 million stems of *L. camara,* which was widely distributed along rivers in the south of the park (Foxcroft and Freitag-Ronaldson 2007). However, the *L. camara* populations have now apparently been substantially reduced, and this switch is most likely due to an unusually large flood in February 2000 (Heritage et al. 2001) that had a profound influence on the vegetation along the river (Foxcroft et al. 2008). When the floods occurred in 2000, large tracts of riparian vegetation, including almost all infestations of *L. camara*, were swept away (Parsons et al. 2006). This result, combined with intensive post-flood clearing, probably allowed ongoing clearing of *L. camara*, combined with biological control, to become much more effective (Vardien et al. 2012). At the same time, however, the flood disturbance probably facilitated the invasion of other species such as *C. odorata* (Foxcroft and Martin 2002, Leroy 2003). No data existed for the effectiveness of *P. hysterophorus* control either, but this species is spreading rapidly and is recognised as a substantial problem in KNP, as elsewhere (Terblanche et al. 2016). Anecdotal (and photographic) evidence can also be cited in support of progress made with the control of aquatic weeds (Fig. 2).

Assessments of the effectiveness of biological control: The effectiveness of biological control in reducing *O. stricta* invasions is among the most documented of control operations in KNP. Within six years of biological control agents being released in 1988, plant biomass declined by about 90% and has since remained at low levels (Hoffmann et al. 1998, Paterson et al. 2011). No other specific studies of the effectiveness of biological control have been carried out in KNP, but based on assessments elsewhere it appears that the invasive shrub *Sesbania punicea* is under complete biological control in KNP (Hoffmann and Moran 1999). Similarly, biological control has made a substantial contribution to the ongoing management of aquatic weeds, where biological control been demonstrated to have effectively suppressed both *Salvinia molesta* and *Pistia stratiotes* elsewhere in the country (Coetzee et al. 2011).

Short-term studies of effectiveness: In a short-term survey of twelve management units in 2007, Morris et al. (2008) suggested that a single clearing operation reduced

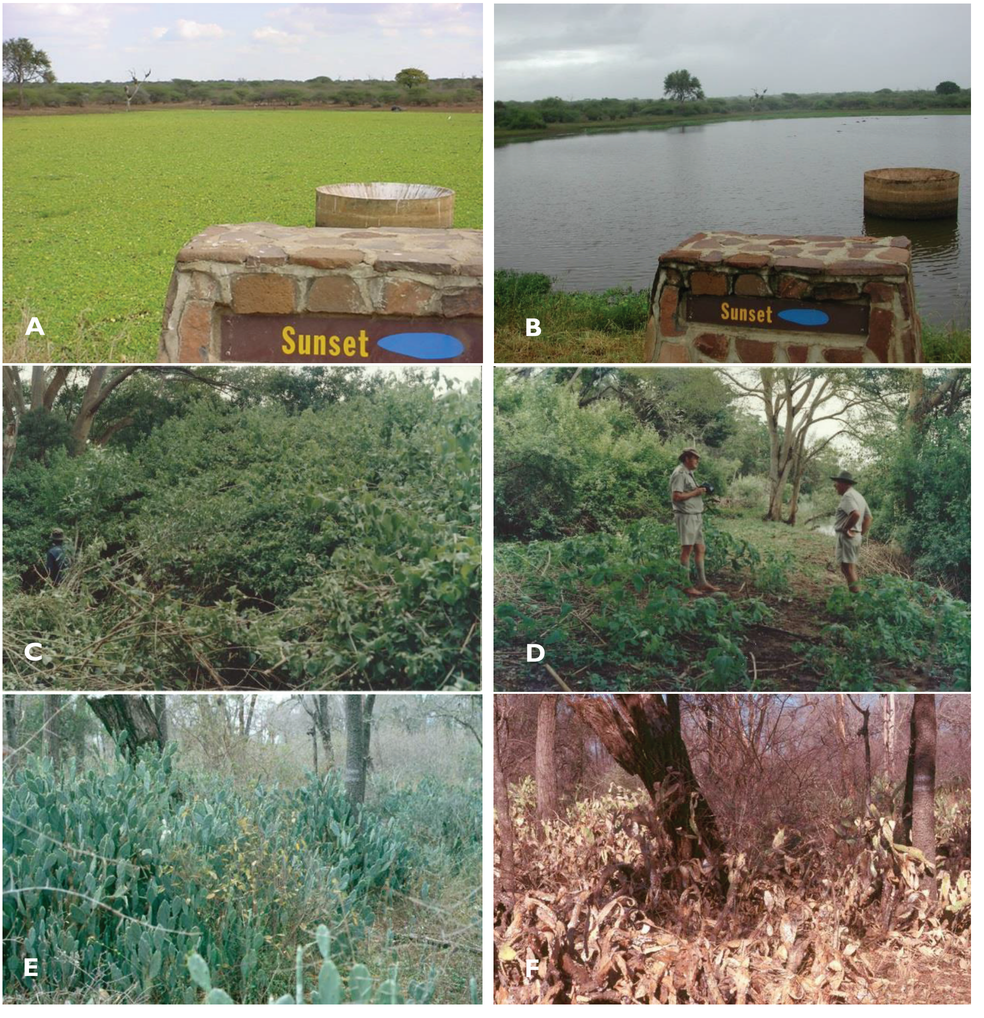

Figure 2. Before and after control of alien plant species in Kruger National Park, South Africa. Sunset Dam was heavily infested by *Pistia stratiotes* (**A**), which was effectively eliminated by a combination of biological and chemical control (**B**). Dense invasions of *Lantana camara* along the Sabie River (**C**) have required intensive mechanical and chemical control to clear (**D**). Populations of *Opuntia stricta* (**E**) have been effectively reduced to low numbers with biological control (**F**).

alien invasive plant densities by 80%. This study concluded that "Continuous clearing acts to effectively limit the establishment and spread of many invasive species despite the ever-present threat of invasion from upstream. Furthermore, the continuous clearing of invasive alien plant stands in KNP ensures that stands are relatively short-lived, preventing long lasting negative impacts on the ecosystem. Removal of invasive alien plant species reduces their disproportionate competitive influence and facilitates the natural re-establishment of native vegetation". This study re-enforces the views of staff above that the densities of some species have decreased.

Genetic studies of source populations: Vardien et al. (2012) used genetics to illustrate that reinvasion of the lower Sabie River in KNP, following the floods of 2000, originated from populations of *Lantana camara* along the tributary Sand River. The Sand River is largely outside of KNP, and was more densely invaded than the Sabie River above the confluence, because of ongoing control on the Sabie that was absent from the Sand River. The study found that re-invasion of the Sabie River below the confluence with the Sand was overwhelmingly from the Sand River populations of *L. camara*. The study concluded that the major flood of 2000 effectively cleared invasive populations of *L. camara* from the riparian areas, and that re-invasion could be attributed to a lack of management outside the KNP, providing evidence of the effectiveness of management in the KNP.

Effectiveness of control of individual species: Based on the experience of the authors, and on the approaches outlined above, it was possible to assign individual species to categories of control effectiveness. Of the 36 species listed in Table 3, four were considered to be under complete control, and a further five were under substantial control. Biological control accounted for all of the species under complete control, and played a role in three of the five species considered to be under substantial control. Control effectiveness was considered to be moderate for two species, and ineffective for five species; control effectiveness for the remaining 16 species could not be assessed with any degree of confidence. Attempts to control annual weeds were all considered to be ineffective.

Costs of control

Over the past 20 years, various organizations have expended almost ZAR350 million (2016 equivalent) on alien plant control operations in KNP (Table 2). Most (84%) of this was funded by public works programs. The largest proportion of public works funding (23%) was spent on the control of *Lantana camara* (Table 3), and most of the funds (61%) were used for clearing outside of the KNP boundary. Just over half (56%) of the funds were expended on species of higher concern, with much less being spent on new incursions with scattered populations (3%; see Table 1 for categories). However, over one third (40%) of the funding was spent on species of lower concern (according to the current classification), of which about half (19% of the total cost of controlling all species) was on annual species of lower concern (Table 3). Because some annual species were regarded as being of higher concern (*Ricinus communis* and *P. hysterophorus*), the amount spent on the control of all annual species was 37% of the total cost. In the case of *Chromolaena odorata*, it is pertinent to note that it was only present as a tiny population in 1997, and it was only once it became more widespread that the spending on this species increased. Had it been present at current densities in 1997, a greater proportion of funding would probably have been directed to its control. The situation is similar for *P. hysterophorus*, although it is a more recent arrival whose spread has been more rapid.

Table 3. Costs and effectiveness of control for selected alien plant taxa in the Kruger National Park. Costs are listed in order of total funds expended per species by public works programs alone between 1997 and 2015 in the Kruger National Park. Cost estimates were not available for aquatic weeds. A proportion of funds were expended outside of the KNP within roughly 10-km of the park boundary. See Table 1 for species priorities, and text for definitions of control effectiveness.

Taxon	Life form	Date first recorded in KNP	Priority	Cost (millions of 2016-equivalent ZAR)		Effectiveness of control
				Inside KNP	Outside KNP	
Lantana camara L.	Perennial shrub	1940	Higher concern (ongoing clearing)	17.4	49.2	Substantial
Ricinus communis L.	Annual shrub	1953	Higher concern (ongoing clearing)	12.8	23.9	Ineffective
Xanthium species, mainly *X. spinosum* L.	Annual forb	1953	Lower concern	15.4	11.6	Ineffective
Senna species, mainly *S. didymobotrya*	Perennial shrub	1952	Lower concern	9.1	11.5	Unknown
Argemone mexicana L.	Annual forb	1932	Lower concern	10.6	7.7	Ineffective
Chromolaena odorata (L.) King & H.E. Robins	Perennial shrub	1997	Higher concern with dedicated control plan	3.6	8.2	Moderate
Datura species	Annual herbs	1953	Lower concern	6.4	5.4	Ineffective
Parthenium hysterophorus L.	Annual herb	2003	Higher concern with dedicated control plan	8.3	3.5	Ineffective
Cardiospermum species, mainly *C. grandiflorum* Sw.	Variable vine	1995	Higher concern (ongoing clearing)	5.3	4.9	Unknown
All other non-priority species	Variable	Variable	Lower concern	3.0	6.3	-
Agave sisalana Perrine	Perennial succulent shrub	1965	Lower concern	0.02	8.1	Substantial
Nicotiana species, mainly *N. glauca* Graham	Perennial shrub	1958	Higher concern (ongoing clearing)	4.9	3.2	Unknown
Solanum seaforthianum Andrews	Perennial vine	1991	Species with scattered populations	2.6	4.5	Unknown
Tecoma stans (L.) Juss. ex Kunth	Perennial shrub or small tree	1950	Lower concern	0.04	5.9	Unknown

Taxon	Life form	Date first recorded in KNP	Priority	Cost (millions of 2016-equivalent ZAR)		Effectiveness of control
				Inside KNP	Outside KNP	
Tithonia diversifolia (Hemsl.)A. Gray	Variable herb or shrub	1953	Higher concern (ongoing clearing)	1.5	3.9	Unknown
Opuntia species (other than *O. stricta*)	Perennial succulent shrubs	1950s	Lower concern	3.8	1.3	-
Melia azedarach L.	Perennial tree	1948	Higher concern (ongoing clearing)	1.0	3.9	Substantial
Psidium guajava L.	Perennial shrub or small tree	1949	Lower concern	0.4	4.2	Unknown
Sesbania species, mainly *S. bispinosa* (Jacq.) W.F. Wight	Perennial tree	1984	Lower concern	1.7	2.3	Complete for *Sesbania punicea* (Cav.) Benth. (biological control); unknown for *S. bispinosa*
Solanum mauritianum Scop.	Perennial shrub or small tree	1954	Higher concern (ongoing clearing)	0.5	3.4	Unknown
Opuntia stricta (Haw.) Haw	Perennial succulent shrub	1953	Higher concern with dedicated control plan	1.1	0.4	Complete (biological control agents redistributed when necessary)
Arundo donax L.	Perennial tall grass	1953	Species with scattered populations	0.3	1.0	Unknown
Agave americana L.	Perennial succulent shrub	?	Higher concern (ongoing clearing)	0.02	0.8	Unknown
Cereus jamacaru DC.	Perennial succulent shrub	1988	Species with scattered populations	0.08	0.4	Complete (biological control)
Dolichandra unguis-cati (L.) L.G. Lohmann	Perennial vine	1965	Species with scattered populations	0.2	0.08	Unknown
Leucaena leucocephala (Lam.) de Wit	Perennial tree	1995	Species with scattered populations	0	0.09	Unknown
Thevetia peruviana (Pers.)	Perennial shrub or tree	1950	Higher concern (ongoing clearing)	0.05	0.03	Unknown
Nerium oleander L.	Perennial shrub	1988	Higher concern (ongoing clearing)	0.03	0.04	Unknown

Taxon	Life form	Date first recorded in KNP	Priority	Cost (millions of 2016-equivalent ZAR)		Effectiveness of control
				Inside KNP	Outside KNP	
Passiflora species, mainly *P. edulis* Sims	Perennial vine	2003	Species with scattered populations	0.0	0.05	Unknown
Cylindropuntia imbricata (Haw.) F.M. Knuth	Perennial succulent shrub	1996	Higher concern with dedicated control plan	0.01	0.01	Substantial (biological control)
Bryophyllum delagoense (Eckl. & Zeyh.) Druce	Perennial succulent shrub	1988	Species with scattered populations	<0.01	<0.01	Unknown
Eichhornia crassipes (C.Mart.) Solms	Aquatic weed	1977	Higher concern	Not available	Not available	Moderate
Pistia stratiotes L.	Aquatic weed	1977	Higher concern	Not available	Not available	Substantial (biological control)
Salvinia molesta D.S. Mitch.	Aquatic weed	1974	Higher concern	Not available	Not available	Complete (biological control agents redistributed when necessary)
Azolla filiculoides Lam.	Aquatic weed	1977	Lower concern	Not available	Not available	Complete (biological control)
Total				110.7	175.8	

Discussion

Current situation

Invasive alien species are regarded as one of the most significant threats to the integrity of KNP (Foxcroft and Freitag-Ronaldson 2007), and this recognition has led in part to the expansion of control programmes (Foxcroft and Freitag-Ronaldson 2007). However, the current KNP management plan (revised in 2008) states that "…alien invasions…are generally currently under reasonable control…" (Foxcroft and Freitag-Ronaldson 2007: 2), and that "The current situation, relating to density and distribution of alien species, is manageable provided careful planning and management remain in place…" (Freitag-Ronaldson and Venter 1996: 54). As outlined above, there is evidence of good progress with the control of several species, notably *Opuntia stricta*, *Sesbania punicea*, *Lantana camara* and several aquatic weeds. The lack of consistent records and monitoring remains a concern, though. As a result there is almost no quantitative evidence that species have been controlled, nor that the measures to control them are appropriate and cost-effective (e.g., Dew et al. 2017), and most assessments (for example those supporting statements in the KNP management plan) come from the undocumented observations of park staff. We would, however, caution against complacency. For example, the relatively recent incursions of the annual weed *P. hysterophorus* into KNP are a cause for serious concern. An isolated recording of the species was first noted in 1991 along the Sand River, and subsequently in a few scattered areas in southern KNP in May 2003. *Parthenium hysterophorus* is an aggressive invader of degraded lands, and it can potentially severely reduce rangeland condition over large areas (Wise et al. 2007). Although there is a dedicated set of protocols for the management of this species in KNP, there has until recently been no monitoring of the effectiveness of management (although this is currently being initiated). As is the case elsewhere in South Africa, the long-term control of this species will probably have to rely heavily on the current efforts to curb further spread and the development of biological control options that will make mechanical and chemical clearing viable (Terblanche et al. 2016).

In addition, although control of invasive alien plants is being achieved within the boundaries for KNP, areas outside of the park remain highly invaded in places (Foxcroft et al. 2007), and thus could continue to act as a source of propagules from which cleared areas in KNP will be re-invaded (e.g. *Lantana camara*, Vardien et al. 2012). Although KNP does operate in a buffer outside of the park, and despite the fact that 61% of available funds were spent outside the park between 2002 and present, the approach faces large challenges, including the need for ongoing negotiation and collaboration between landowners and government agencies. Finally, the expenditure of a large proportion of funds on species of lower concern (especially some annual species) continues to reduce the overall efficiency of the control programme. The focus on annual species has come about for a variety of possible reasons, including the imperative to create employment (annual weeds provide accessible populations for control), the conviction among several managers that they are harmful (but like almost all invasive alien plants, there is no documented evidence of this, see Blackburn et al. 2014), and the fact that annual weeds have not until recently been formally recognised as species of lower concern. In the light of these concerns, we have identified a number of core alien plant control program components that require attention in the interests of improving KNP's invasive alien plant management program, which may provide concepts that can benefit other similar situations.

Planning, goal-setting and monitoring

The practice of setting realistic and achievable goals, based on an agreed set of priorities, the development of plans to achieve these goals, and regular monitoring of outcomes are widely accepted as essential elements of management (Genovesi and Monaco 2013). However, aside from a general goal of maintaining native biodiversity by preventing or controlling alien plant invasions, the KNP's management plans contain no specific measurable objectives or detailed plans for achieving them. The system of using of thresholds of potential concern to guide management interventions is largely aimed at highlighting any changes to a species' situation, and triggering action in response, but it is not designed to guide the management of alien plant invasions that require systematic treatment over multiple years. The practice of allocating available funds to different areas and species without setting clear goals is a widespread shortcoming that has been reported in other parts of the country (Fill et al. 2016; McConnachie et al. 2012, van Wilgen et al. 2012, 2016, Kraaij et al. 2017). The situation could be substantially improved by prioritising the areas to be worked in, setting achievable goals for the control of priority species in priority areas in the MUCPs, practicing conservation triage to ensure that scarce funds are utilised effectively, and expanding the monitoring program to include ecological outcomes in addition to employment creation, disbursement of funds, and areas treated (van Wilgen et al. 2016).

Determining priorities

While KNP has assigned priorities to a number of alien plant species, the allocation of funds to these species did not always reflect these priorities. In particular, a substantial proportion of funding was expended on annual weeds, many of which were later recognised as being of lower priority. Most annual weeds (with the possible exception of *P. hysterophorus*) have not been demonstrated to be harmful, and are only invasive in disturbed areas, including naturally dynamic habitats such as riparian zones or heavily grazed sites. The fact that there are so few studies that document the harmful effects of invasive alien plant species (Jeschke et al. 2013) makes it very difficult to arrive at consensus regarding priorities, and prioritization exercises are consequently influenced predominantly by perceptions. Alien species are regarded as undesirable because they can change biotic interactions and processes in their new range, but many alien species apparently have little or no detectable effects of their new environment (Blackburn et al. 2014). In KNP, the annual shrub *Ricinus communis* is regarded as a priority, even though it never covers large areas at a local scale, i.e. it does not develop into the extensive monocultures associated with other invasive alien species such as *L. camara*, *C. odorata* or *P. hysterophorus* in similar habitats elsewhere in Africa (A.B.R. Witt, Pers. Comm.). Nonetheless, an estimated ZAR 36.7 million has been expended on this species (more than any other species except *Lantana camara*, Table 3), as it is widely perceived as harmful despite a lack of evidence. In addition, given the dual goals of public works projects, funds can be allocated to particular projects to create employment in some areas, rather than to meet ecological goals (van Wilgen and Wannenburgh 2016), leading to further inefficiencies, although we are not able to quantify the degree to which this happens in KNP.

Three responses to this situation seem appropriate. First, it is clear that more studies need to be done to assess the degree of impact associated with individual invasive alien species on which substantial funds are being expended. The resources for conducting these impact assessments should not be sourced from management funds, but rather from the KNP research budget (van Wilgen et al. 2016). Management should be ongoing, but can shift its focus if and when assessments indicate that such a shift would be warranted. Incursions of new alien species can be dealt with without an impact assessment, as control costs would be low, and waiting for a full impact assessment would allow the species to spread, potentially increasing control costs exponentially. Secondly, it would be useful to formally document the criteria used to assign priorities to invasive alien species, so that management can focus on defensible priorities. In this regard, it would be useful to apply the framework developed by Blackburn et al. (2014), which employs the mechanisms of impact used to code species in the International Union for Conservation of Nature (IUCN) Global Invasive Species Database. Finally, although difficult decisions are going to be required, it would seem crucial to re-direct funding to those species that clearly pose greater threats, and for which other solutions (such as biological control) are not an option. Some of these funds could also be used to control alien plant populations outside of KNP, so as to reduce the risk of re-invasion of cleared areas.

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