Developing thresholds of potential concern for invasive alien species: Hypotheses and concepts

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ABSTRACT

The Kruger National Park (KNP) has developed and refined a system of management called 'strategic adaptive management' (SAM), which rests on the concept of 'threshold of potential concern' (TPC). TPCs represent end-points in a continuum of change. When thresholds are reached – at which point concerns of negative impacts on biodiversity are raised – management options are explicitly considered and implemented. This paper describes the TPCs developed for monitoring and managing invasive alien species (IAS). More importantly, however, it describes the conceptual understanding, principles and hypotheses adopted as the foundations for setting these TPCs. In accordance with adaptive management practices, the TPCs will be revised as the ecological and conceptual understanding of invasions grows and information is gained through research in the KNP and elsewhere.

Conservation Implication: In accepting that species and systems are variable, and that flux is inevitable and desirable, these TPCs developed for invasive alien species specifically, provide end points against which monitoring can be assessed. Once a threshold is reached, the cause of the threshold being exceeded is examined and management interventions recommended.

INTRODUCTION

New paradigms in ecology stress complex adaptive systems and heterogeneity (Biggs & Rogers 2003; Pickett, Cadenasso & Benning 2003). However, embracing a new ecological paradigm requires a new approach to management that accepts and deals sensibly with ecosystem flux. The threshold of potential concern (TPC), as developed by the Kruger National Park (KNP), provides a measurable end-point in the management paradigm in use in the KNP, namely strategic adaptive management (SAM). SAM is a variation on the widely used concept of adaptive management (Allee 1997; Biggs & Rogers 2003). However, an important philosophical departure of SAM from standard adaptive management practice is the focus on 'forward' or 'strategic thinking' and predictive assessment. TPCs thus form an important component of SAM, representing goals against which the success of ecosystem management can be measured. Biggs and Rogers (2003) provide a succinct definition of TPCs: 'those upper and lower levels, along a continuum of change in selected environmental indicators that provide the basis for decisions on the acceptability of that change'. The TPC approach allows for fluctuations in the ecosystem but highlights exceedances in ecosystem change over defined space and time scales, thereby defining the desired set of conditions of the system being managed. Thus TPCs, in effect, provide an indication of whether management actions are currently, or preferably, are predicted to in future have an unacceptable impact on biodiversity (biodiversity structure, function and composition; Noss 1990). It is important to note here, however, that the TPCs developed for invasive alien species (IAS) represent only an upper limit (threshold), as the lower threshold implies the absence of alien species.

A central tenet of adaptive management is 'management by experiment' (Rogers 2003). Thus, TPCs form the basis of an inductive approach to SAM, as they are invariably hypotheses of the limits of acceptable change in ecosystem structure, function and composition (Rogers 2003). They are therefore a compatible and well-articulated set of adaptive management end-points (Biggs & Rogers 2003). As such, their validity and appropriateness are always open to challenge and they must be adaptively modified as understanding and experience of the system being managed increase (Biggs & Rogers 2003). An important aspect of TPCs is that they are pre-agreed goals, and consensus has thus already been reached on possible sets of future actions once TPCs are reached. This therefore implies that management is prevented from stalling or procrastinating at such point. When a TPC is reached or, preferably, when modelling predicts that it will be reached, it prompts an assessment of the causes of the extent of change (Biggs & Rogers 2003). In this manner, the exceeded TPC represents 'one dimension of the composite desired envelope represented by all the objectives together' (Biggs & Rogers 2003).

In providing a detailed description of the current TPCs and their underlying hypotheses, I first describe the KNPs 'management by objectives' approach. I then explore the scientific basis of each TPC and its criteria, providing some ideas for future work and the integration of invasive species impacts into the overall biodiversity TPCs.

DISCUSSION

Management by objectives

The KNP management plan is arranged in a series of objectives, cascading down from the higher, coarser level objectives to the lower, ground level goals (Du Toit, Rogers & Biggs 2003; Foxcroft 2004; Foxcroft & Downey 2008). The revised objectives provide for a holistic approach to invasive-species management (KNP 2005) and include all alien species. I deliberately use the term 'alien' as opposed to various synonyms, such as 'exotic', due to the potential confusion that they create (Pyšek *et al.* 2004; Richardson *et al.* 2000). Alien plants are defined as 'taxa in a given area whose presence there is due to intentional or unintentional human involvement, or which have arrived there without the help of people from an area in which they are alien'. Invasive plants are 'a subset of naturalized plants that produce reproductive offspring, often in very large numbers, at considerable distances from the parent plants, and thus have the potential to spread over a large area'. Subsets of invasive species, which change the character, form or function of the ecosystem over a substantial area, are termed 'transformer species' (Pyšek *et al.* 2004; Richardson *et al.* 2000).

Placed under the *ecosystem objective* of the KNP (see KNP 2005), the main aim of the *alien impact objective* is 'to anticipate, prevent entry and where feasible and/or necessary control IAS in an effort to minimize the impact on, and maintain the integrity of indigenous biodiversity'. For the purposes of the KNP and building on the above-mentioned definition of alien species, 'any species or organisms which have been introduced into, or entered the KNP on its own accord, from outside its borders' are considered alien.

The implication of this is that:

1. any species from outside the boundaries of South Africa is considered alien (except in the case of the Mozambican and Zimbabwean sections of the Transfrontier Conservation Area, which is a natural extension of the KNP ecosystem);
2. any species that may be indigenous to South Africa but that does not occur within the KNP ecosystem is considered alien to the KNP ecosystem; and
3. any species within the KNP that moves from one particular landscape to another where it does not occur naturally is considered alien to that landscape.

Although the list of objectives is described fully in KNP (2005; also see http://www.sanparks.org/parks/kruger/conservation/scientific/mission/managementplan.php), the five main *alien impact objectives* are summarised here. These objectives closely follow the principles advocated by international best-management practice standards (Wittenberg & Cock 2001; 2005):

- Objective 1: *Strategy and support*: To develop a long-term strategy for the management of IAS by evaluating the current and projected future overall scale of threat, by addressing organisational and infrastructural capacity, by developing policy and by building support for continued high-level commitment.
- Objective 2: *Prevention*: To anticipate and evaluate imminent or potential risks (the likelihood of invasion and the likely impact of invasion) to the KNP and pathways of invasion and to develop effective mechanisms to monitor, manage or mitigate these.
- Objective 3: *Control*: To ensure the effective and timely development and implementation of integrated control strategies in such a manner that both rapid response and long-term maintenance goals are met.
- Objective 4: *Research*: To promote and develop a coordinated research programme to develop a clearer understanding of the dynamics and the impacts of alien-species invasions.
- Objective 5: *Awareness*: To develop an awareness programme to inform and educate SANParks staff and visitors on especially the dangers and consequences of IAS to facilitate global IAS initiatives.

The current TPCs therefore link directly to the *prevention* and *control* objectives in that acceptable limits for the spread of a species are set. The *research* objectives involve the development of programmes to evaluate the impacts of invasions at various scales and alien-species abundance (density).

Scientific principles for the basis of TPCs

The principle that the KNP is not an island and is substantially impacted on by actions beyond its borders is a central tenet of the understanding and management of alien-species invasions

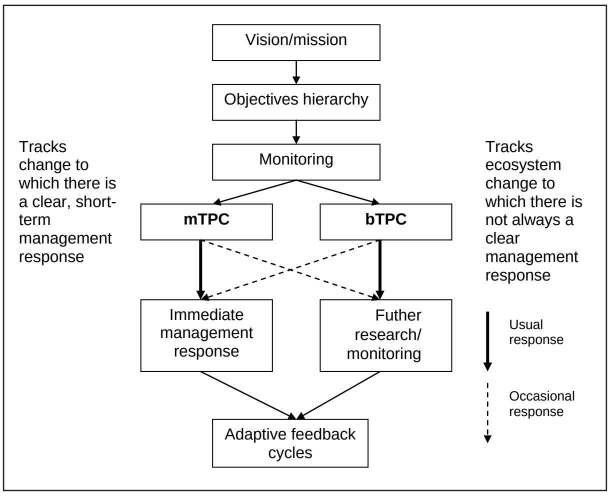

FIGURE 1
Relationship between TPCs aimed at management and TPCs aimed at detecting change in biodiversity or ecosystem function and structure

(Foxcroft, Rouget & Richardson 2007). Working in concert with this is the acceptance of the role of temporal flux and spatial heterogeneity within the ecosystem (Pickett, Cadenasso & Benning 2003; Rogers 2003). This needs to be embraced in the context of invasions as well (Foxcroft 2004). Although desirable, the eradication or control of all alien species is neither feasible nor practical. Fluxes in the spread and abundance of alien-species populations must thus be accepted, even though this is contrary to most alien-species management ideals. Although invasions by alien species are normally considered to be unidirectional in that they progress from an initial founding population to becoming widespread transformer species, this is the exception rather than the rule. Most species, whether naturalised or invasive, fluctuate to some extent depending on drivers, such as rainfall and disturbance. While most managers concerned with alien species strive to eradicate or manage all alien species and to suppress the populations as close to zero as possible, we contend that this approach is not possible either in the KNP or (generally) anywhere else. This is due mainly to the size of the KNP and to the number of species present. We suggest that management will be more effective by focusing its resources on the most problematic species only and in the areas where they are becoming problematic. As long as the species are present at below acceptable thresholds for a determined period, the species should not be a management priority. The TPC system allows for fluctuation, including of alien species, but highlights critical 'turning points' where concern is raised about the possible negative effects of aliens on biodiversity (Foxcroft 2004).

The invasive-species TPCs, while already having undergone revision (Biggs & Rogers 2003; Foxcroft 2004; Foxcroft & Downey 2008; Foxcroft & Richardson 2003; Freitag-Ronaldson & Foxcroft 2003), do not yet specifically address the direct and measurable negative impacts on biodiversity. The current TPCs instead represent operational or management thresholds of potential concern (mTPCs) (Figure 1). A well-articulated set of mTPCs complements bTPCs by having a short-term, immediate management response to an assumed impact.

The mTPCs follow a conceptual understanding of the process of biological invasions (Richardson *et al.* 2000) and highlight changes in distribution within and on the KNP boundaries (Figure 2).

The invasion of an alien species into an area follows a general pattern in which the species overcome a series of barriers that impedes the invasion of some species and that results in a smaller subset becoming transformer weeds (Foxcroft, Parsons & McLoughlin 2008). Each stage in the process presents

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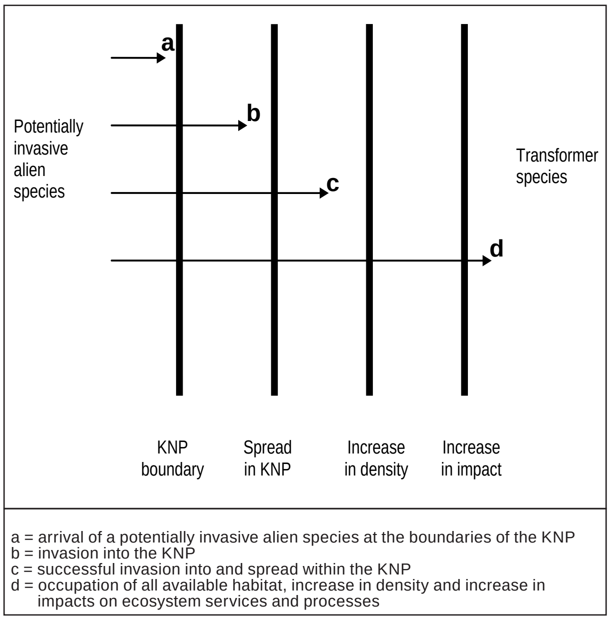


FIGURE 2
Model hypothesis underpinning the development of TPCs for understanding invasion processes in the KNP (This framework follows the model approach by Richardson *et al*. 2000)

the KNP with a particular threat and suggests appropriate management actions. This therefore means that the thresholds focus on the alien species rather than on their negative impacts on biodiversity. This further means that the negative biodiversity impacts are implied and that the presence of alien species is unacceptable to the biodiversity conservation values of SANParks.

The use of TPCs to raise management concerns does not, however, mean that control operations can now be stopped and carried out only when a TPC is reached. To the contrary: normal management operations aimed at the maintenance of a species at a low abundance or at the containment of a species at its current distribution require ongoing follow-up operations to be successful and are a critical element in the overall control programme. Only at a low abundance (or limited distribution) can we assume that a species is having little impact on the system and can we thus allow the idea of flux in alien-species distribution and abundance. The TPC should highlight only when and where this may be exceeded and should then require specific, targeted action. This may be compared to the management of fire in the KNP. Rangers initiate patch burns as an ongoing management activity (in the same way that alien plants are controlled on an ongoing basis) to achieve appropriate levels of heterogeneity in (among other variables) patch size and fire intensity (in the same way that alien-plant control aims to prevent negative impacts on biodiversity by preventing high abundances of alien plants), which are framed as the various TPCs (Van Wilgen, Govender & MacFadyen 2008). Exceeding these thresholds results in an assessment of the cause and of appropriate action and perhaps in a change to the management approach.

The first invasive-species TPCs (Foxcroft & Richardson 2003) provided a list of various criteria for evaluation. These included 1) a new distribution in the KNP or an increase in distribution, 2) an increase in density, 3) the rate of spread versus the rate of clearing, 4) impact on biodiversity and 5) outside alien threats (Foxcroft & Richardson 2003). Experience, however, highlighted the need to adapt the system due to repeat exceedances of the same TPCs. In other words, the TPC system was not able to deal sensibly with repeat invasions that were no longer cause for the same level of concern. This led to the development of multiple-level TPCs to avoid raising 'false alarms' (Foxcroft 2004) or, in other words, to rationalise them into a series of graded practical challenges that are feasible to handle in practice and that are still meaningful in a conservation ecology sense (see Table 1 for a sample of TPCs exceeded to date and Table 2 online supplementary for the full list).

The main hypothesis behind developing TPCs for IAS is that alien species represent a threat to the biodiversity of the KNP and that, if left unmanaged, will cause substantial – often irreversible – biodiversity or economic loss (McNeely *et al*. 2001; Mooney *et al*. 2005; Pimentel *et al*. 2005). The principles adopted for the development of these mTPCs are further captured in the 'barriers' model by Richardson *et al*. (2000). Using this approach, the 'points of concern' are reflected as the barriers to invasion and the next level of TPC is invoked to overcome the barriers (Figure 2). As a species approaches the KNP, management's response is to prevent this introduction (point **a** in Figure 2). This entails, where possible, the KNP controlling the population itself, partnering with institutions such as provincial alien-clearing projects (Working for Water, for example, which is a national programme that aims to control alien plants to prevent impacts on water resources, economic and social impacts and impacts on biodiversity; see also Van Wilgen, Le Maitre & Cowling 1998) or entering into cooperative agreements with landowners. Once the species has invaded the KNP, the spread of the species is examined against the next level of TPC, where eradication (if possible) or containment strategies are called into force (point **b**). There may, however, be examples where the tabling of a TPC (formally recording the exceedance of a TPC and placing it on the management agenda; see also Foxcroft & Downey 2008) leads to a well considered 'do nothing' option. Theoretically, the third level of TPC is invoked once all available habitat has been invaded. At this point, the main concern is the abundance of the species (point **c**). Although a species may not have expanded its range to include the entire available habitat in the KNP, however, it is assumed that, at a local scale, patches have reached a density that may have some level of impact on biodiversity (its composition or function) in that particular area (point **d**).

Although all the TPCs are nested within the framework outlined above, the following section discusses the hypotheses and theory behind each TPC criterion.

Level 1 TPCs

TPCs that deal with new invasions of a species in the KNP (Figure 3a).

Criteria:

- Imminent external threat (a species on the park boundaries which is believed by most experts to be able to invade within 12 months).
- First-ever record in the KNP.

Principles:

1. The introduction of any new alien species is contrary to the mandate of SANParks (Foxcroft, 2006; KNP, 2005).
2. The potential negative impacts of biological invasions far outweigh the risk that the alien species will be benign (see, for example, Mooney *et al*. 2005 and the numerous references therein).
3. A 12-month period of likely entry into the KNP provides sufficient time to develop management strategies and control the population appropriately outside the KNP. This should, however, be considered per species and adjusted accordingly where necessary.

Level 2 TPCs

TPCs that deal with an increase in the distribution of a species (or of all species combined) in the KNP over a 12-month period (Figure 3b).

TABLE 1
Sample of alien species TPC exceedances to date

Date	TPC level*	TPC detail	Species of concern	Management response	Expected outcome at the time of the TPC notification and current status
Oct. 1999	Multi-level TPCs not in use	Imminent outside threat to the KNP (Crocodile River)	*Chromolaena odorata* (Chromolaena)	Special Working for Water contract issued to have the localised patch of plants eradicated	The aim was to eradicate the patch of plants but it soon became evident that it could not be completely removed and it therefore became part of a long-term, ongoing management programme
Sept. 2007	2	First-ever records in a new grid cell (Olifants River)	*Opuntia stricta* (sour prickly pear)	Chemical control and surveys to determine whether the plants have already spread	The eradication of the patches of plants but long-term monitoring for regrowth and re-invasion from sources in the upper Olifants River catchment

*Level 2: TPCs that deal with an increase in the distribution of a species (or of all species combined) in the KNP over a 12-month period

Criteria:
- First-ever record from a new grid cell.
- Any new grid cell invaded that is not contiguous with the previous distribution.
- The expansion of invasive species through contiguous grid cells representing more than a 5% increase over the number of grid cells recorded as invaded in the reference (base) year.

Principles:
1. The early detection of new incursions of invasive species allows timely response and potential for eradication. This principle is widely accepted (Wittenberg & Cock 2001; 2005) as a standard procedure for the successful control of invasions. Studies further suggest that, once an invasion has increased to an area of over 100 ha, the chances for eradiation are minimal (Rejmánek & Pitcairn 2002). The increase of propagule pressure reaches a critical mass at some stage, at which point management is compromised. This is based on the 'long-fuse, big bang' theory, which states that, although a build-up of alien species may initially be slow, it is followed by a rapid and exponential increase in the population and propagative individuals and is seldom manageable once this point is reached (Chapman, Le Maitre & Richardson 2001; Wilkinson 1995).
2. The eradication of newly formed invasion foci increases the probability of the invasion being contained at its current extent (Moody & Mack 1988). Although the criteria stated above were already determined in the first iteration of alien-species TPCs, only the 'first ever record from a new grid cell/area' TPC was used.
3. Although the expansion and contraction of alien species are expected to occur through natural processes and disturbances, such as floods, droughts and the resulting change in succession (the acceptance of a flux paradigm), the total area of the invasion should not be allowed to increase above a stated maximum tolerable 'ceiling' level from the base scenario. This level is currently set at 5% but it is an estimate and requires refinement.

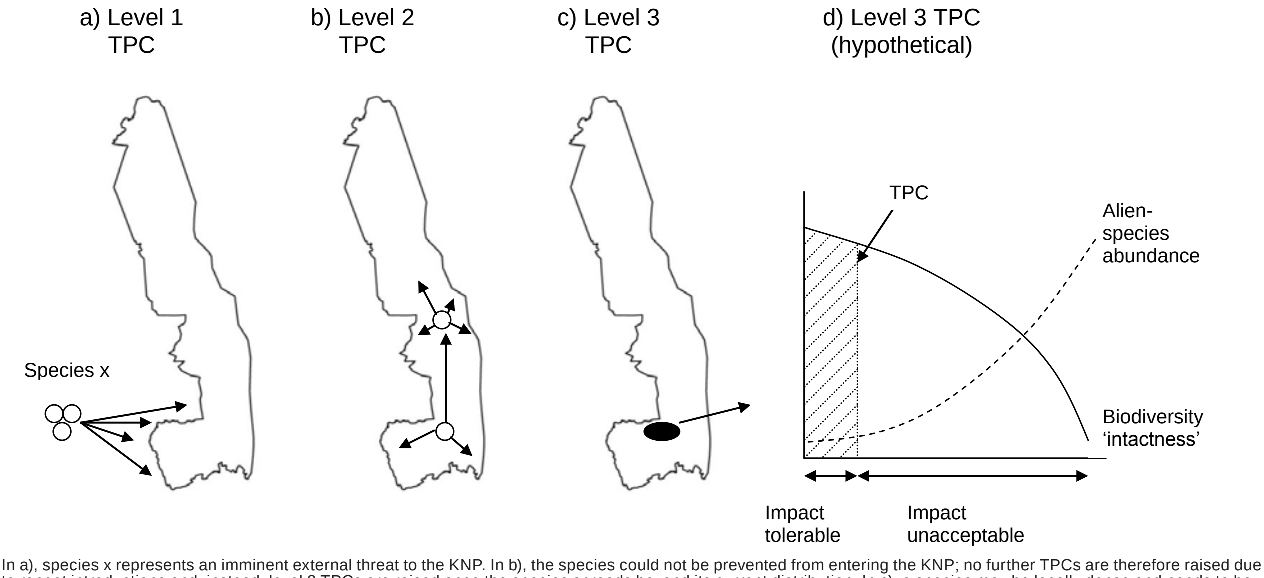
Level 3 TPCs

TPCs that deal with an increase in the density of a species (or of overall alien-species density) in the KNP (Figure 3c and d). These TPCs are not yet operational, however, due to the lack of data and an efficient cost-effective monitoring option to date. They are nonetheless described hypothetically and may have the potential to be used as surrogates for biodiversity impact TPCs in future if research is able to relate species abundance to unacceptable impacts.

Criteria:
- Any increase by two or more density classes in any grid cell.
- Any increase of one density class upwards of 'medium density' in any grid cell.

Density (or apparent density) is currently measured in the following classes but will be reviewed as monitoring options are evaluated (Le Maitre & Versfeld 1994):

- Rare: The plants are present but at very low densities, occurring here and there; density = 0.01%
- Occasional: The plants are widely spaced, occurring here and there, on average, more than 10 canopy covers apart; density = 0.02 – 1%



In a), species x represents an imminent external threat to the KNP. In b), the species could not be prevented from entering the KNP; no further TPCs are therefore raised due to repeat introductions and, instead, level 2 TPCs are raised once the species spreads beyond its current distribution. In c), a species may be locally dense and needs to be monitored to ensure that it does not exceed the predefined density limit d), at which point negative biodiversity impacts (a decrease in biodiversity intactness) are expected.

FIGURE 3
Spatial presentation of the barriers indicated in Figure 2

- Very scattered: The plants average 3 to 10 canopy diameters apart; density = 1.1 – 5%
- Scattered: The plants average 1 to 3 canopy diameters apart; density = 5.1 – 25%
- Medium: There are clear and plenty of gaps between the canopies of the plants, and other vegetation is still present and vigorous, the plants averaging 0.3 to 1 canopy diameters apart; density = 25.1 – 50%
- Dense: There are small gaps between the canopies of the plants, there is no canopy overlap and other vegetation is still present, the plants averaging 0.1 to 0.3 canopy diameters apart; density = 50.1 – 75%
- Closed: The canopies of the plants are closed, touching or overlapping, and other vegetation is generally suppressed, sparse or lacking, the plants averaging less than 0.1 canopy diameters apart; density > 75%

Hypothesis:
An increase in the density of invasive species leads to a negative impact on indigenous biodiversity, whether in terms of composition, function or structure. This hypothesis has not, however, been tested in the KNP and only arbitrary density values have been assigned as evaluation criteria thus far.

Future work

In order to detect changes in distribution or abundance, a spatially explicit dataset with reasonable coverage is required to set the baseline from where changes can be evaluated. This is a substantial challenge for an area the size of the KNP (which is approximately 20,000 km^2 in extent). The KNP has fortunately, however, been developing a spatially explicit dataset that covers the KNP and that contains about 28,000 data points (Foxcroft 2008b). This has been possible due largely to the use of CyberTracker units (handheld PDA/GPS devices with customised software), which are deployed daily by rangers during their patrols (Foxcroft 2008b). Due to the extent of the area that needs to be covered, however, it is believed that the data will be representative of the real levels of invasion only by about 2009/2010, from when changes can then be plotted. This will require the problem of the scale at which change in species distribution is detected being resolved (Foxcroft 2008b). Once this has been done, all species records can then be assigned to a grid cell and the data of subsequent years can be overlaid on the base year, allowing the TPC criteria to be assessed.

This, however, deals only with the TPCs that evaluate spatial distribution. The level 3 TPCs, which deal with change in the abundance of species, require further work 1) to develop a monitoring programme that provides the necessary data to evaluate these TPCs and 2) to be able to relate particular abundances to negative impacts on biodiversity. From this, we can develop new 'biodiversity impact' or biodiversity thresholds of potential concern (bTPCs) that either directly or through the use of appropriate surrogates address the issue of the negative impacts of alien species on biodiversity. These would ultimately replace the currently used level 1 and 2 TPCs. This was highlighted in the alien-impact section of the objectives hierarchy as an important avenue of future research (KNP 2005). A start on this has already been made through research that aims to quantify impacts on selected biodiversity indicators, such as the impact of *Opuntia stricta* (the sour prickly pear) on spiders and beetles as indicator species. It clearly still needs to be expanded, however, to measure impacts on other ecosystem components, such as ecosystem services and provisions, and for other alien species. Useful studies have been done on the water-use impacts of invasive-plant species and on various land-use practices (such as commercial forestry using alien trees; for examples, see Le Maitre, Versfeld & Chapman 2000; Le Maitre *et al.* 2001; Versfeld, Le Maitre & Chapman 1998). We also need to develop the ability to express impacts in terms of biodiversity loss due to alien species in the KNP system.

CONCLUSION

The development of TPCs for the management of invasive species presents an approach to management that is fundamentally proactive in nature. The system allows for ecosystem flux but within predefined thresholds of acceptability. Although the current TPCs represent a pragmatic approach to a substantial biodiversity concern (that of IAS) over a vast area, further development is needed. Ideally, TPCs need to be developed that highlight the point at which IAS present a measurable threat to the biodiversity composition, function or structure of an area.

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TABLE 2
List of alien species TPC exceedences to date

Date	TPC level[1]	TPC detail	Species of concern	Management response	Expected outcome at the time of the TPC notification and current status
Oct. 1999	Multi-level TPCs not in use	Imminent outside threat to the KNP (Crocodile River)	*Chromolaena odorata* (Chromolaena)	A special working for water contract was given to have the localised patch of plants eradicated	The aim was to eradicate the patch of plants, but it soon became evident that the patch would not be completely removed. *C. odorata* become part of a long-term, ongoing management programme
Oct. 1999	Multi-level TPCs not in use	New record in the KNP- plants observed at Sunset Dam and Orpen Dam	*Azolla filiculoides* (red water fern)	Introduction of biological control agents	Long-term, ongoing control using biocontrol agents
Nov. 1999	Multi-level TPCs not in use	New distribution in the KNP and an increase in distribution (Luvuvhu and Limpopo River systems)	*Oreochromis niloticus* (Nile tilapia)	To support the efforts of the provincial conservation authorities to curb the dispersal of these fish. To monitor the increase in distribution of the fish. To research the genetic mixing of *O. niloticus* and *O. mossambicus* (indigenous species)	Management / control of a fish species is unlikely in most situations, although further spread through anthropogenic means should be prevented. However, information is needed on the potential impacts to the ecosystem and other related species
Mar. 2000	Multi-level TPCs not in use	New distribution within the KNP (N'waswitshaka firebreak, Skukuza)	*Agave sisalana* (Sisal)	Detailed survey of the area and chemical control of the plants	The aim was to eradicate this patch of plants. While the plants appear to be eradicated, periodic site visits are still carried out
Mar. 2000	Multi-level TPCs not in use	Increase in distribution in the KNP (new records of both species along the Skukuza – Lower Sabie road)	*Senna occidentalis* (wild coffee) and *Senna bicapsularis* (rambling Cassia)	Detailed survey of the roadsides and mechanical / chemical control of the plants	Although the aim was to eradicate the plants this was found to be unfeasible and the sites still require ongoing control
May 2000	Multi-level TPCs not in use	New occurrence of an invasive alien plant species within the boundary of the KNP (near Skukuza)	*Helianthus annuus* (Sunflower) and *Nicandra physaloides* (Apple of Peru)	Survey of the area for additional plants and physical removal	As there were only one plant of each species found, they were removed and it was felt unlikely that either species had established populations in the KNP
July 2000	Multi-level TPCs not in use	Imminent outside threat to the Crocodile River	*Tithonia diversifolia* (Mexican Sunflower)	*T. diversifolia* was added to the list of species targeted by the alien plant control teams	Ongoing control is required, as it is unlikely that this species will ever be eradicated
Oct. 2000	Multi-level TPCs not in use	Imminent outside threat (Malelane)	*Acridotheres tristis* (Indian myna)	Requested provincial conservation authorities to control the myna's. Requested all staff to report observations of myna's in the KNP	Myna's are closely associated with human settlements and are likely to increase in numbers in towns bordering the KNP. Myna's found in the KNP should be destroyed.
Sept. 2000	Multi-level TPCs not in use	Imminent outside threat to the KNP, (Hans Merensky Country Club, Phalaborwa).	*Chromolaena odorata* (Chromolaena)	Control efforts were required to start immediately (mechanical / chemical). Ongoing monitoring and follow-up work	The aim was to eradicate the patches of plants, but it was unlikely that these plants could be eradicated and would have to form part of ongoing follow-up operations
Sept. 2000	Multi-level TPCs not in use	Any new occurrence of an invasive alien plant species within the boundary of the KNP, (on the tributary of the Tshutshi spruit, Phalaborwa)	*Chromolaena odorata* (Chromolaena)	Control efforts were required to start immediately (mechanical / chemical). Ongoing monitoring and follow-up work	The aim was to eradicate the patches of plants, but it was unlikely that these plants could be eradicated and would have to form part of ongoing follow-up operations
Nov. 2000	Multi-level TPCs not in use	New occurrence in the KNP- reported from Numbi and Shitlave, Pretoriuskop region	Varroa (bee) Mite	Ongoing monitoring	Unknown, potentially large impacts on bee colonies
Dec. 2000	Multi-level TPCs not in use	New distribution in KNP (Talamati and Lower Sabie)	*Acridotheres tristis* (Indian myna)	Requested provincial conservation authorities to control the myna's. Requested all staff to report observations of myna's in the KNP	Myna's are closely associated with human settlements and are likely to increase in numbers in towns bordering the KNP. Myna's found in the KNP should be destroyed
Feb. 2001	Multi-level TPCs not in use	Increase in distribution of a species in the KNP (Mlondozi Dam, N'waswitsontso River and Sabie River)	*Cardiospermum halicacabum* (Balloon Vine)	Survey of the areas invaded and *C. halicacabum* to be added to the list of species controlled	*C. halicacabum* to form part of the ongoing maintenance control work in the KNP
Feb. 2001	Multi-level TPCs not in use	New occurrence of an invasive alien plant species within the boundaries of the KNP (two small patches at Pafuri and Vlakteplaas)	*Arundo donax* (giant reed)	Plants to be manually removed and any coppice to be sprayed with an appropriate herbicide	These small patches were to have been eradicated. While it appears that they have been eradicated, periodic site visits are still carried out
June 2001	Multi-level TPCs not in use	New distribution in the KNP and an increase in distribution (Olifants and Crocodile Rivers)	*Hypophtalmichthys molitrix* (Silver carp)	To support the efforts of the provincial conservation to curb the dispersal of these fish. To monitor the increase in distribution of the fish.	Management / control of a fish species is unlikely in most situations, although further spread through anthropogenic means should be prevented. Information is however needed on the potential impacts to the ecosystem and other related species
Oct. 2002	2	First occurrence from a new grid cell and any new grid cell invaded that is not contiguous with grid cells invaded previously- numerous patches along the Luvuvhu , Letaba, Klein Letaba, Olifants, Sabie and Crocodile Rivers	*Chromolaena odorata* (Chromolaena)	Continued surveys, monitoring and increased vigilance to determine the extent of the distribution of these plants. Immediate control of all plants. A number of regional workshops. An internal scientific report.	Control and containment of the plants still continues
May 2003	2	First ever record from a new grid cell (or new area)- Gutchwa Spruit and Nsikazi River	*Eichhornia crassipes* (water hyacinth)	Chemical control of plants upstream of the KNP and biological control for plants from the KNP boundary downstream.	Eventual eradication of the plants outside the KNP and containment / long-term biological control of the plants inside the KNP

Online supplementary Table 2 (Cont...)

Date	TPC level[1]	TPC detail	Species of concern	Management response	Expected outcome at the time of the TPC notification and current status
May 2003	2	First ever record from a new grid cell (or new area)- roadsides in the Crocodile Bridge and Lower Sabie areas	*Parthenium hysterophorus* (parthenium)	Ongoing mapping / surveying. Develop research projects on the potential spread and impacts of *P. hysterophorus*. Chemical control.	Containment of the plants at the current sites. While much research and distribution mapping has taken place, little chemical control has been done
May 2003	2	First ever record from a new grid cell (or new area)- Sabie river, near Skukuza	*Colocasia esculenta* (elephants ears)	The two patches of plants to be removed through manual (digging) means. Follow-up by means of herbicides	The aim was eradication of these two patches of plants. It appears that the patches have been eradicated, although periodic site visits are still required
May 2003	2	First ever record from a new grid cell (or new area)- numerous dams and rivers in the KNP	*Aplexa marmorata*; *Physa acuta*; *Lymnaea columella* (Alien snails)	Follow-up survey in 5 years time and research to be initiated on the potential impacts of the snails	Control unlikely, but an understanding of the potential impacts is necessary
July 2003	3	Increase in density at Engelhard Dam	*Eichhornia crassipes* (water hyacinth)	Biological control of the Makhadzi Spruit and chemical control on the main body of Engelhard Dam	Long-term sustainable control largely through the use of biocontrol. Chemical control has continued to be used as an integrated management option on Engelhard dam
July 2003	1	New occurrence of a species in the KNP- Pafuri region	*Australocylindropuntia cylindrical*	Chemical control	Eradication of this species from the KNP. Periodic site visits are still required
Sept. 2003	1	New occurrence of a species in the KNP- Malelane, Crocodile River	*Tarebia granifera* (snail)	Monitoring of spread, research on possible future impacts	Control unlikely, but an understanding of the potential impacts is necessary
Oct. 2003	2	Increase in distribution in the KNP-Skukuza animal holding bomas	*Acridotheres tristis* (Indian myna)	Control if possible and removal of nests if necessary	Eradication of birds at this site (the bird disappeared shortly after tabling this TPC)
Oct. 2003	2	Increase in distribution – Crocodile river. Although *E. crassipes* had previously been known to occur in the Crocodile River, it had been absent since the floods of 2000.	*Eichhornia crassipes* (water hyacinth)	Integrated control using Biological control at selected sites and aerial application of herbicides as dam walls and weirs	Long-term integrated control
Feb. 2004	1	New occurrence of a species in the KNP- Crocodile Bridge	*Harrisia martinii* (moon cactus)	Chemical control and follow-up operations to ensure patch is eradicated. Surveys to determine how far the plants have spread. Landowner in adjacent property (source) to control the plants as well	Although the aim was eradication of the patch of plants, ongoing site visits will still be required
Feb. 2004	2	Increase in distribution in the KNP-Crocodile Bridge	*Bryophyllum delagoense* (mother of millions)	Chemical control and follow-up operations to ensure patch is eradicated. Surveys to determine how far the plants have spread. Landowner in adjacent property (source) to control the plants as well	Although the aim was eradication of the patch of plants, ongoing site visits will still be required
Feb. 2004	2	Increase in distribution in the KNP-Crocodile Bridge	*Opuntia stricta* (sour prickly pear)	Chemical control and follow-up operations to ensure patch is eradicated. Surveys to determine how far the plants have spread. Landowner in adjacent property (source) to control the plants as well	Although the aim was eradication of the patch of plants, ongoing site visits will still be required
Mar. 2004	1 & 2	Tabling TPC of bTB introduction and spread within the KNP	*Mycobacterium bovis* (bTB)	Ongoing monitoring of spread and prevalence per herd and region; detection of bTB in other species; containment at the human / wildlife interface	To develop long-term control methods
July 2004	2	First ever record from a new area (Crocodile River)	*Pistia stratiotes* (water lettuce)	Determine the extent of the invasion, survey for the presence of biocontrol agents and release agents if necessary	Long-term control using biological control agents
July 2004	1	Re-invasion of a controlled species- Mtshawu Dam. This species was previously completely controlled by the biocontrol agents and absent from the dam as from late 2001	*Salvinia molesta* (Kariba weed)	Re-release of the biological control agents	Unlikely that eradication will take place. Ongoing monitoring and if necessary re-release of the biological control agents, to ensure a long-term control programme
Dec. 2004	2	First ever record from a new area-Phabeni, Sabie River	*Thelechitonia trilobata* (Singapore daisy)	Chemical control	Ongoing chemical control operations to eradicate these patches from the Sabie River, and prevent re-introduction from further upstream in the Sabie River. Ongoing site visits continue
July 2005	2	First ever record from a new grid cell- Tshokwane	*Opuntia imbricata* (imbricate cactus)	Chemical control of the plants and surveys to ensure any plants that have started to spread are also controlled	Eradication of this patch of plants. Although the plants appear to have been eradicated, ongoing site visits will be required
Oct. 2005	2	First record in new grid cells (patches along the Sabie River, just upstream from Kruger Gate)	*Arundo donax* (giant reed)	Plants to be manually controlled and coppice to be sprayed with an appropriate herbicide	This invasion will require ongoing follow-up as part of routine operations, as it is unlikely that these patches will be eradicated

Online supplementary Table 2 (Cont...)

Date	TPC level[1]	TPC detail	Species of concern	Management response	Expected outcome at the time of the TPC notification and current status
Oct. 2005	1	Imminent external threat (a species on the boundary of the KNP which might invade within the next 12 months)- Sabie River, Hazyview area	*Acacia decurrens* (green wattle)	Mechanical / chemical control of the trees in Hazyview. Survey between the plants and the KNP boundary	Although this patch can be eradicated, it is likely that there is a larger source somewhere in the upper catchment and continued vigilance is required
Sept. 2007	2	First record in new grid cell (small patch of plants near Olifants tourist camp)	*Cereus jamacaru* (Queen of the night)	Plants to be chemically controlled with an appropriate herbicide	This small patch should be eradicated, but will require ongoing site visits
Sept. 2007	2	First ever records in a new grid cell- Olifants River	*Opuntia stricta* (sour prickly pear)	Chemical control and surveys to determine whether the plants have already spread	Eradication of the patches of plants, but long-term monitoring for re-growth and re-invasion from sources in the upper Olifants River catchment

[1]Level 1: TPCs that deal with new invasions of a species in the KNP.
Level 2: TPCs that deal with an increase in distribution of a species (or all species combined) in the KNP, over a 12 month period.

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