Diversity and Distributions, (Diversity Distrib.) (2009) **15**, 367–378

BIODIVERSITY RESEARCH

Patterns of alien plant distribution at multiple spatial scales in a large national park: implications for ecology, management and monitoring

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ABSTRACT

Aim Spatial scale is critical for understanding and managing biological invasions. In providing direction to managing alien plant invasions, much emphasis is placed on collecting spatially explicit data. However, insufficient thought is often given to how the data are to be used, frequently resulting in the incompatibility of the data for different uses. This paper explores the role of spatial scale in interpreting, managing and monitoring alien plant invasions in a large protected area.

Location Kruger National Park, South Africa.

Methods Using 27,000 spatially-explicit records of invasive alien plants for the Kruger National Park (> 20,000 km^2) we assessed alien plant species richness per cell at nine different scales of resolution.

Results When assessing the patterns of alien plants at the various scales of resolution, almost identical results are obtained when working at scales of quarter-degree grids and quaternary watersheds (the fourth level category in South Africa's river basin classification system). Likewise, insights gained from working at resolutions of 0.1–0.5 km and 1–5 km are similar. At a scale of 0.1×0.1 km cells, only 0.4% of the Kruger National Park is invaded, whereas > 90% of the park is invaded when mapped at the quarter-degree cell resolution.

Main conclusions Selecting the appropriate scale of resolution is crucial when evaluating the distribution and abundance of alien plant invasions, understanding ecological processes, and operationalizing management applications and monitoring strategies. Quarter-degree grids and quaternary watersheds are most useful at a regional or national scale. Grid cells of 1 to 25 km^2 are generally useful for establishing priorities for and planning management interventions. Fine-scale data are useful for informing management in areas which are small in extent; they also provide the detail appropriate for assessing patterns and rates of invasion.

Keywords

Alien plant distribution, biological invasions, conservation, exotic plants, non-native species, Kruger National Park, management, monitoring.

INTRODUCTION

The negative impacts of biological invasions are among the foremost concerns facing conservation managers (Mooney *et al.*, 2005). In an effort to provide strategic direction to management interventions, much emphasis is placed on the collection of spatial data (Ewel *et al.*, 1999; Hulme, 2003; Dark, 2004; Guisan & Thuiller, 2005; Wittenburg & Cock, 2005). Unfortunately, insufficient attention is often given to how the data are to be used (Pyšek & Hulme, 2005). The result is that the spatial resolution and scale of data collection may be inappropriate for particular uses.

Plant ecologists have long recognized the importance of sampling scale in their descriptions of dispersal or species distributions (Wiens, 1989), and have paid much attention to scale in understanding rarity (Hartley & Kunin, 2003). Far less attention

DOI: 10.1111/j.1472-4642.2008.00544.x
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has been given to scale issues in understanding the dimensions of biological invasions (but see Higgins *et al.*, 1996, 2001).

In a biogeographical sense, invasions are the opposite of rarity (range expansion versus range contraction, although being rare does not automatically imply undergoing range contraction) (Van Kleunen & Richardson, 2007). Considerable insights for setting conservation priorities have emerged from studies of scale dependency of rarity and extinction risk (Hartley & Kunin, 2003). Similar insights are needed for managing invasive species, where management options depend on various features in the range, some of which may only be detected at a particular grain (grain refers to the individual units of observation, often expressed as grid cells; Turner *et al.*, 1989).

This also has implications for the information value of data collect at different levels of spatial resolution. Understanding all facets of spatial pattern is more complicated for invasive alien species than for native species because the former are still in the process of filling their potential range and have not sampled the full range of available habitats (Rouget *et al.*, 2004; Wilson *et al.*, 2007). Few studies have evaluated the processes and patterns of invasion from the initial founder population to the point where all available, susceptible habitats have been sampled (Pyšek & Hulme, 2005). Furthermore, only 10% of invasion studies focus on the initial stages of dispersal while the remainder focus on widespread and advanced invasions (Puth & Post, 2005). Invading plants also have spatial and temporal dynamics that are difficult to predict (Pyšek & Hulme, 2005), frequently expanding their distribution from extremely low numbers in source populations, often through rare dispersal events (Puth & Post, 2005; Trakhtenbrot *et al.*, 2005). However, our ability to predict ecological phenomena such as patterns of alien plant distribution, and thus infer ecological processes (Turner, 1989), depends on the relationship between spatial and temporal scales of variation (Wiens, 1989). With an increase in spatial scale (increasing coarseness of grain), important processes operate at longer time scales, time lags are longer, and indirect effects become increasingly important. Also, understanding patterns of invasions is also a function of both the extent (the overall area of the investigation) and the grain of the investigation (Wiens, 1989). Therefore, the various components of scale (time, extent and grain) of the investigation determine the range of patterns that we detect and the explanations we can derive from them.

Studies on biological invasions that integrate across different scales are rare (Pyšek & Hulme, 2005) because of the difficulties of collecting enough data over a sufficiently large area, and capturing infrequent, long-distance dispersal events, with which to explore these problems (see also Richardson *et al.*, 2004; Trakhtenbrot *et al.*, 2005). Invasive species rarely disperse across the landscape in a continuous front (Pyšek & Hulme, 2005), and opportunistic dispersal events, or secondary invasion foci, are frequently disproportionally important in driving spatial expansion (Foxcroft *et al.*, 2004). If distributions are mapped at fine grain, such small outlying patches, which may be crucial invasion foci, can be identified, whereas such essential information is lost at a coarse grain (Wiens, 1989; Rouget & Richardson, 2003). Different types of information are captured in data measured at different spatial scales, and there is no way for insights to be readily transferred from one spatial scale to another. Consequently, such collections of information are frequently of limited use to managers, planners and policy makers (Rouget & Richardson, 2003; Barnett *et al.*, 2007).

We suggest that only by carefully assessing spatial patterns of plant invasions at scales ranging from a plot to the landscape and to the region can we understand the full range of processes that interact to structure the distribution of invading plants (Rouget & Richardson, 2003; Richardson *et al.*, 2004). Unfortunately, few parts of the world are well suited for such assessment of plant invasions at multiple spatial scales. This is because most ecosystems are fragmented, with complicated patterns of anthropogenic influence that substantially increases the complexity of understanding the determinants of invasion patterns. Large protected areas provide a useful arena for exploring issues relating to the role of scale and the dimensions of geographical range (Turner *et al.*, 1989). However, few protected areas have been suitably mapped at a sufficiently fine grain, over a large extent. We propose that South Africa's Kruger National Park (KNP) provides a unique opportunity to explore the links between distribution pattern and spatial scale for invasive alien plants. KNP (*c.* 20,000 km^2 in extent) is one of the largest protected areas in the world that is actively managed for biodiversity conservation, and for which very detailed data on the distribution of the distribution of invasive alien plants is available (spatially explicit data comprising nearly 27,000 records with excellent coverage across the whole park).

Our aims were to assess the implications of spatial scale in developing an understanding of the distribution of invasive alien plants, to (1) propose important features of scale that need forethought in collecting and managing invasive alien plant data for holistic management interventions and (2) assess whether we can determine the minimum grain of data that is required to fulfil the above requirements.

METHODS

Study area and priority species

Protected areas are habitat islands – natural landscapes and habitats surrounded by various culturally modified systems (Pickett & Thompson, 1978). KNP also shares the increasing global concerns over invasive alien species (Rejmánek *et al.*, 2005), to the point where these are now regarded as one of the most pressing threats to the biodiversity of the park (Freitag-Ronaldson & Foxcroft, 2003). A number of pathways of plant invasion have been described in detail for KNP, including rivers (Foxcroft *et al.*, 2007) and intentional introductions for ornamentation in staff villages and tourist accommodation (Foxcroft *et al.*, 2008). In other protected areas, vehicles (Lonsdale & Lane, 1994) and roads (Bennet, 1991; Tyser & Worley, 1992; Gelbard & Belnap, 2003) have also been shown to be important pathways of invasion in protected areas. Both are implicated in the spread of invasive species in KNP (Freitag-Ronaldson & Foxcroft, 2003) but have not been studied in detail in KNP.

Figure 1 Sources of alien plant distribution data; (a) in relation to Kruger National Park (KNP) infrastructure and rivers, (b) KNP alien biota section alien plant distribution data, (c) *Opuntia stricta* distribution data, and (d) alien plant distribution data from the CyberTracker programme. The insert places KNP in relation to the rest of South Africa.

Kruger National Park (Fig. 1a) is situated in the north-eastern lowlands of South Africa, bordering Mozambique and Zimbabwe. Extending 360 km from north to south, 90 km east to west at its widest point, and covering about 20,000 km^2, KNP is one of the largest areas in the world managed primarily for biodiversity conservation (Foxcroft & Richardson, 2003). KNP occurs in southern Africa's savanna biome and has 20 main vegetation types (Mucina & Rutherford, 2006) overlying a gentle topography, which ranges from 110 to 850 m above sea level. Details of the physical environment, the biotic components and ecosystem function of KNP appear in du Toit *et al*. (2003). Information on alien plant invasions and management interventions are found in Foxcroft & Richardson (2003), Freitag-Ronaldson & Foxcroft (2003) and Foxcroft & Freitag-Ronaldson (2007).

KNP is situated in the mid-reaches of seven extensive drainage systems (namely the Limpopo, Luvuvhu, Shingwedzi, Letaba, Olifants, Sabie, Crocodile Rivers), flowing from the higher lying reaches in the west, to Mozambique in the east. All the watersheds are invaded to some extent, with 192 invasive alien plant species being recorded in the upper watersheds of KNP (Foxcroft *et al*., 2007). To date, 373 alien plant species have been recorded in KNP (Foxcroft *et al*., 2003); these records include ornamental aliens, ruderal species and widespread invasive aliens.

While management has evolved and priorities have changed over time (see Foxcroft & Freitag-Ronaldson, 2007 for a synopsis), recent efforts have focused on chemical and later biological control of *Opuntia stricta* var. *dillenii* (Cactaceae; sour prickly pear), mechanical/chemical control of riparian species (such as *Lantana camara*; Verbenaceae; common lantana), and removal of ornamental alien plants in staff and tourist villages. Although reasonable progress has been made, additional efforts including prevention, early detection and rapid response, maintenance control, regular policy revision and research are required to deal with the escalating problems. These elements are all included in the current management plan for KNP (KNP, 2005).

Data collection

Alien plant records and distribution data have accumulated over many years and from several different sources. The first seven records of alien plants in KNP were made in 1937 (Obermeijer, 1937). Although early records were accompanied by general

Table 1 Sources of alien plant distribution data for the Kruger National Park. IAS = invasive alien species.

Source data base	Number of records	Number of alien species	Years covered	Data type	% of alien records in overall data set	Method of collection
KNP CyberTracker	2982 (pres) 1,965,910 (abs)	8*	2004–2006	P/A	0.14	GPS/Palm (CyberTracker); ranger patrols
Opuntia stricta	19,849	1	2000–2003	P	100	GPS/Palm (CyberTracker); GPS records manually captured. Systematic survey, described in Foxcroft *et al.* (2004)
General IAS	4118	162#	1974–2005	P	100	GPS records manually captured. Ad hoc data from KNP alien biota section, herbarium, rangers, field guides. Some of this data is described in Foxcroft *et al.* (2003)

*Includes some 'spp.' records, for example '*Opuntia* spp.' for which plants were not identified to the species level, Data type – whether data include presence and absence points or presence records only.

descriptions of localities, the advent of increasingly accurate Global Positioning Systems (GPS) has led to more precise locality data. The three main sources of data are: (1) the records of the KNP alien biota section (Fig. 1b); (2) a species-specific (*Opuntia stricta*) data set (Fig. 1c); and (3) a large set of locality-precise data collected by park rangers on their patrols (CyberTracker; Fig. 1d and Table 1). The data from the KNP alien biota section comprise mainly *ad hoc* records collected during various field trips and from herbarium and other records. The species-specific distribution data on *O. stricta* was collected over the species' entire range in KNP, to guide management strategies (Foxcroft *et al.*, 2007a,b) and for research on the spread dynamics of the species (Foxcroft *et al.*, 2004). The CyberTracker system (see http://www.cybertracker.org) was developed for application in conservation management, as a user-friendly interface for PalmOS computers linked to GPS units (see also DiPietro *et al.*, 2002; McNaught *et al.*, 2006). The system allows personnel (including semiliterate field workers) to record customised observations with GPS coordinates. The potential use of the CyberTracker system for collecting ecological data in KNP was recognized in 2000 and the system was rapidly incorporated into KNP procedures for testing and further development. Up to 120 CyberTracker units are currently deployed on daily patrols across the KNP. Observations, including animal and plant sightings, water and fire management records and other types of data are recorded on each patrol. The alien plant species observations include *Lantana camara*, *Opuntia* spp. (Cactaceae), *Chromolaena odorata* (Asteraceae, chromolaena), *Senna* spp. (Fabaceae), *Pistia stratiotes* (Araceae, water lettuce) and *Xanthium* spp. (Asteraceae). Rangers email data files to the central KNP Geographic Information Systems (GIS) Lab where the data are collated, cleaned, summarized and made accessible to users. The KNP CyberTracker data currently comprises over 1.97 million records collected between 2004 and 2006. Almost the entire KNP has been sampled at least once, with priority areas (in terms of rangers patrol requirements) being sampled much more often (Fig. 2).

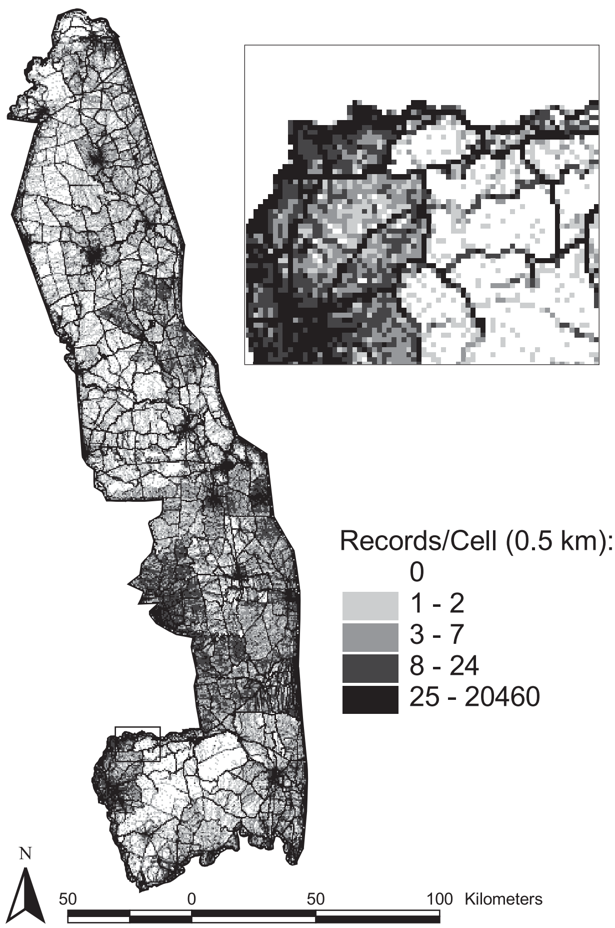

Figure 2 Distribution of Kruger National Park (KNP) CyberTracker data plotted as records/0.5 × 0. 5 km cell. These data are collected by KNP rangers on aspects such as water, fire and poaching management (amongst others) and are used as null records for assessing alien plant distribution. The insert shows a detailed view of the point records.

Figure 3 The distribution of the four most abundant invasive alien plant species in Kruger National Park; (a) *Opuntia stricta*, (b) *Lantana camara*, (c) *Chromolaena odorata* and (d) *Parthenium hysterophorus*.

The combined alien plant distribution data set includes 26,949 records (Table 1). Although the data cover 162 species, 70% of the records are for a single species, *Opuntia stricta*, which was systematically surveyed for a specific purpose (Foxcroft *et al.*, 2004). The earliest records with detailed locality data date from 1974 (*Salvinia molesta*, Salviniaceae, Kariba Weed), while most of the data were collected from 2000 onwards. The four most abundant species were *Opuntia stricta, Lantana camara, Chromolaena odorata* and *Parthenium hysterophorus* L. (Asteraceae, parthenium) (Fig. 3a–d). These four species alone accounted for 81% of the occupied cells at the largest cell size we used (551 km^2), and 0.33% of the cells occupied at the 0.1×0.1 km cell size (Table 2). With the CyberTracker programme (with integrated GPS units) being widely used, the area surveyed has substantially increased. At a fine grain (0.1×0.1 km) there is an average of 1.03 records (null/absence records for alien plants) per watershed or cells (Table 2). At the coarser scale (for example, in cells of 25×27 km) there are up to 39,900 records per cell (null/absence records for alien plants; Table 2).

A limitation of all three data sets is that not all alien plant species are equally represented or equally well surveyed. For example, the CyberTracker has extremely accurate and comprehensive data for a few species, whereas the *O. stricta* data focus on one species which is mapped in detail (i.e. individual plants and discrete patches; see Foxcroft *et al.*, 2004). The data from the alien biota section include many species, but with few records for most species. The data do not include any measure of abundance for each locality (although some measures of abundance can be inferred from the density of observations, with the caveat that some species are more conspicuous than others). Despite these limitations, we know of no other data set with records for as many species with such a fine resolution over such an extensive area for any protected area in the world.

Although there has been a large long-term management programme (Foxcroft & Freitag-Ronaldson, 2007), no populations of alien plants are known to have been eradicated. In the best-case scenario, some alien plant populations have been reduced in abundance/density. We are therefore confident that the data provide an accurate picture of the real situation in KNP and that ongoing clearing programmes have not had a substantial influence on the distribution patterns.

Mapping alien plants at multiple spatial scales

As we were interested in understanding perspectives of alien plant invasions at various scales and making recommendations for management and monitoring, we mapped the alien plant species distribution at nine different levels of grain (Table 2). This ranged from point locality data, to 1×1 km grid cell resolution, to the quarter-degree grid reference system (approximately 25×27 km at the latitude of KNP) which is commonly used for survey data in South Africa (for examples relating to invasive

Table 2 Summary of attributes per grid cell size. There are a total of 26,949 alien plant records and 1,965,910 absence points for the Kruger National Park (KNP).

Cell size (km)*	Cell area (km^2)	Total number of cells in KNP	% of cells invaded	% cells occupied by four main species§	Mean (maximum) species richness/cell	SD of species richness/cell	Mean number records/cell (including absence)
0.1	0.01	1,904,673	0.41	0.33	0.005 (23)	0.08	1.03
0.25	0.06	306,222	1.35	0.99	0.02 (23)	0.2	5.20
0.5	0.25	77,162	3.11	2.00	0.04 (23)	0.3	25.48
1	1	19,602	7.18	4.12	0.1 (24)	0.7	100.29
2	4	5053	16.03	8.41	0.4 (31)	1.4	389.06
5	25	872	41.97	20.07	1.5 (49)	3.8	2254.48
QW†	ave 551	49	91.84	81.63	12.8 (71)	13.4	38,263.76
QDS‡	675	51	90.20	72.55	11.4 (72)	13	39,905.86

*Cell size indicates the length of the cell side, for example 1 × 1 km. †QW – Quaternary watershed (quaternary watersheds are nested subdivisions within primary, secondary and tertiary watersheds and are used for regional-scale planning for many environmental initiatives in South Africa, such as the national Working for Water programme which is responsible for invasive alien plant control. The average size of the QW in the KNP is 551 km^2 (Foxcroft *et al.*, 2007). ‡QDS – Quarter-degree square (15′ latitude × 15′ longitude, representing roughly 25 × 27 km at the latitude of the study area, Rouget *et al.*, 2004). §The four most abundant species (number of records) in the KNP include *Opuntia stricta* (20,029 records), *Lantana camara* (2059 records), *Chromolaena odorata* (302 records) and *Parthenium hysterophorus* (204 records). SD, standard deviation.

plants, see Henderson, 1998, 1999; Rouget *et al.*, 2004; Foxcroft *et al.*, 2007) and the quaternary watershed (fourth level category in South Africa's river basin classification system).

All spatial analyses were carried out using ARC GIS or Arcview 3.2. Grids of various resolutions were prepared (in grid and polygon format) and each cell was provided with a unique identifier value. For each of these grids, we determined the alien plant species richness and the number of records per cell and then generated maps at various resolutions. We also assessed the extent to which the 'absence' data (from the full CyberTracker data set) were distributed across KNP, in order to assess survey bias and sampling effort. The CyberTracker data set is the only data set for which we can infer true absence points, because for each feature (animal sighting, water point and fire scars, among others) a GPS point is recorded, and we assume that if an alien plant had been present at that particular point that it would have been recorded (for the species that the rangers specifically survey).

The successful application of ecological theory to management practice (including monitoring) demands an understanding of the linkages among different ecological scales (Wiens, 1989; O'Niell *et al.*, 1991). However, ecologists still struggle to understand these linkages, let alone transfer this knowledge to practice (Edwards *et al.*, 2002; Rouget & Richardson, 2003). To gain insight into this problem, we assessed our data qualitatively at nine different scales. We randomly selected one quaternary watershed with high alien species richness and one quaternary watershed with low species richness, with which to contrast insights gained from assessing the different scales. Within each of these units one cell at a finer scale was selected, for both high and low species richness, respectively. We then discuss the implications for understanding ecological processes in the invasion process, managing and monitoring plant invasions.

RESULTS

Mapping alien plants at multiple spatial scales

A frequency distribution diagram (Fig. 4a–h) provides interesting insight into the pattern of species richness per cell. The quarter-degree cell and quaternary-watershed scale (Fig. 4a,b), not surprisingly, show similar (normal) distribution patterns, as they are similar in extent (675 km^2 and 551 km^2, respectively). However, it is important to note that although the area of the quaternary-watershed scale varies slightly, it is more ecologically meaningful when considering functions related to rivers or riparian corridors. The 5 × 5 km cell, 2 × 2 km cell and 1 × 1 km cell (Fig. 4c–e) have similar shape distribution curves, while cells at the 0.5 × 0.5 km, 0.25 × 0.25 km and 0.1 × 0.1 km resolution (Fig. 4f–h) have similar patterns. We can thus infer that similar insights into understanding alien plant patterns may be gained from working at three broadly similar units, namely, 500–700 km^2, 1–25 km^2 and 0.01–0.25 km^2 (Table 2).

The range of cell sizes we selected corresponds to a substantial difference in the number of cells across the KNP. For example, at the 0.1 × 0.1 km cell size, there are 1.9 million cells in KNP, while there are only 51 cells at the scale of quarter-degree grid cells (Table 2). This corresponds to a range of 0.4% and 90% of the cells being invaded, respectively, substantially altering the perceived level of invasion across the landscape.

The CyberTracker data base presents a unique spatial data set, covering an extensive area. The full richness of the data set will only emerge over time as the data are explored from a number of perspectives. We used the full data set to represent absence (null) records for alien plants and to test whether there were any areas that had been substantially under- or oversurveyed. While there

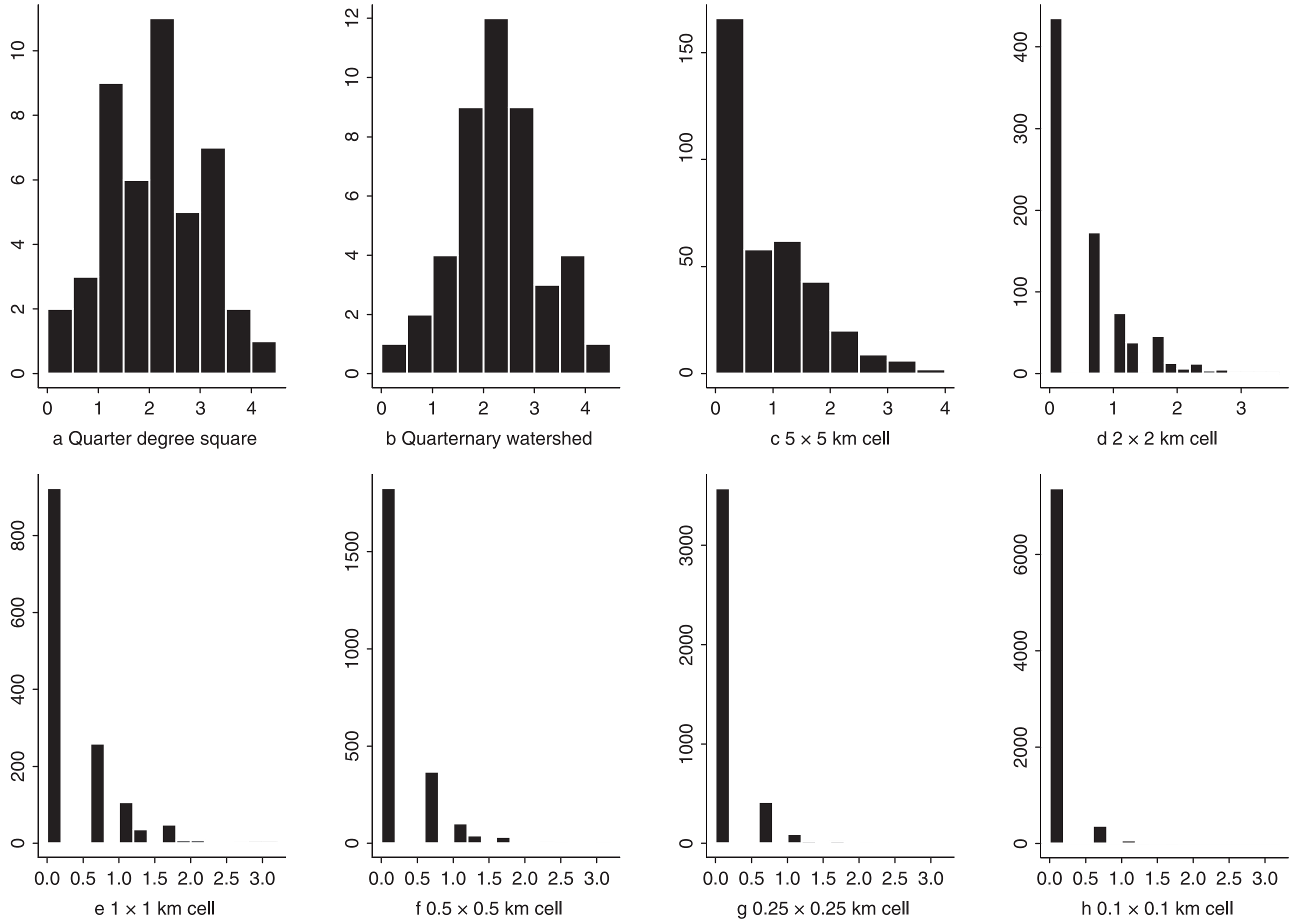

Figure 4 Frequency distribution of alien plant data in the Kruger National Park at eight scales of resolution.

is an average of 39,000 records for the quarter-degree square (QDS) scale, more importantly, we find a mean of 1.03 records per cell for the 0.1 × 0.1 km cell size (Table 2). This indicates that at the finest scale of resolution for which we evaluated alien plant richness data, almost every cell was visited at least once.

We plotted the alien plant species richness for each cell size in order to assess the spatial patterns (Figs 5, 6). Although the pattern of invasion is similar across the 0.1 to 0.5 km scales (Fig. 5a–c), this differs substantially from those of 1–5 km (Fig. 5d–f), altering the perceived level of invasion in KNP. The level of invasion suggested by two vastly different scales, for example, 0.1 × 0.1 km cells (Fig. 5a) and 5 × 5 km cells (Fig. 5f), would leave the reader with the impression that the southern KNP is either hardly, or severely invaded. The loss of resolution is also clear as the size of the cells increases, loosing crucial information about specific outlying populations. Consider for example, the straight line of records running north-south in the south eastern KNP, where in Fig. 5(a–c) (0.1 to 0.5 km cells), the distribution of the patches is clearly distinguished, but completely lost in Fig. 5(d–e) (1 to 5 km cells).

Working at a scale of a quaternary watershed or quarter-degree cell (Fig. 6a,b) substantially altered perceptions of the level of invasion in the KNP, although the shape of the watersheds provides some insights into which river systems or catchments are priority areas generally. However, comparing the patterns in Figs 6(b) and 5(a) clearly shows that much information is lost about the detailed nature of the invasion.

By qualitatively assessing our alien plant distribution data (Figs 7 and 8), we gained insights for three important aspects of plant invasions: ecological understanding, monitoring and management (Table 3). As each cell is sequentially examined at a finer scale, nested within the next, the usefulness of the particular scale for any of the three components (ecology, monitoring and management) emerges. The management and ecological usefulness of each scale are usually opposite. Coarser scales are generally more useful for directing management interventions (Table 3, levels a and b), and finer scales more useful for research into aspects such as examining plant distribution patterns and predictive distribution modelling, where features of the environment can be closely related to the distribution patterns of the plants (Table 3, levels e and f). However, due care is also required here. In Fig. 8 we selected a quaternary watershed with low species richness, indicating that although present in low numbers, the entire watershed appears invaded to some degree. However, at a finer resolution (Fig. 8e) it is evident that there are very low numbers of plant records, which define the category for the entire

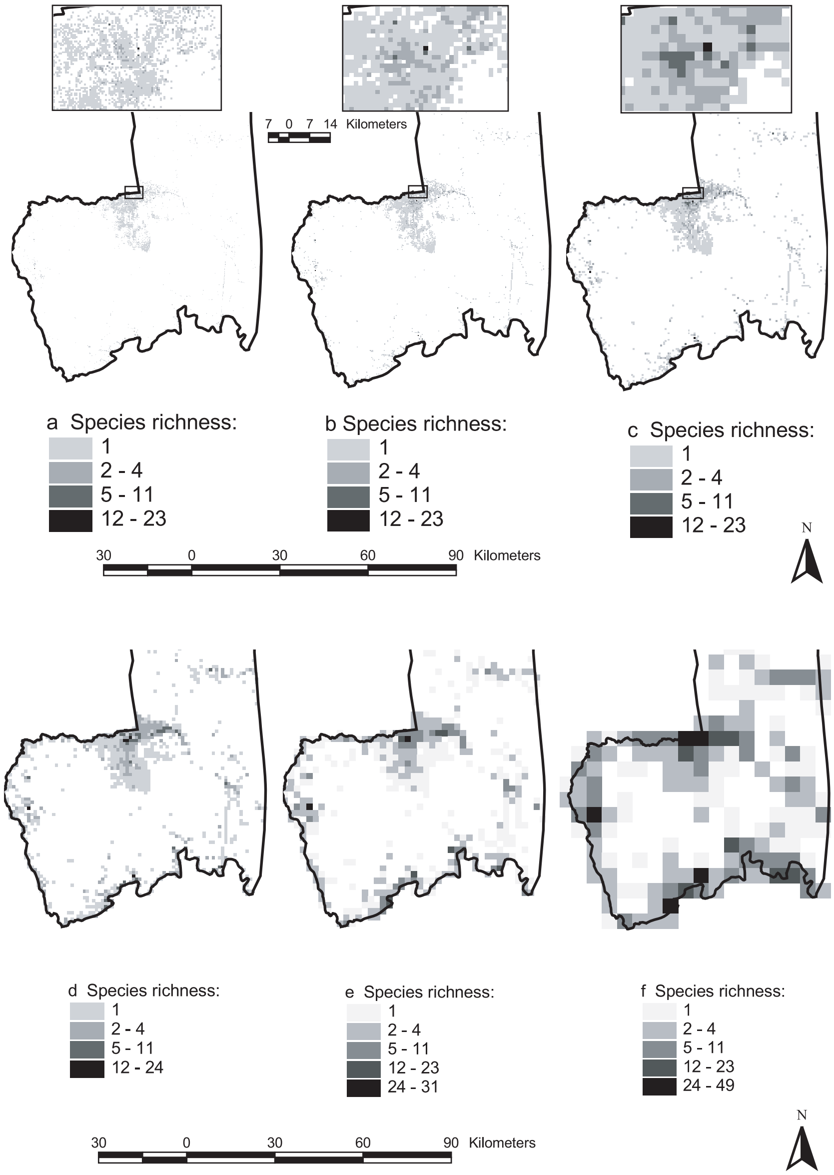

Figure 5 Alien plant richness data for the southern Kruger National Park, at (a) 0.1×0.1 km scale, (b) 0.25×0.25 km scale, (c) 0.5×0.5. The inserts provide a more detailed view of the data for each scale.

watershed at a coarser level. Determining the scale at which monitoring – referred to here as the ability to detect changes in species distribution and species density/abundance over time – should take place is more difficult and relates to the extent of the area. At the extent of KNP, general changes in density can be detected at coarser scales (Table 3), but it is unlikely that detailed information can be gained for changes in species distribution at these scales. In areas of smaller extent, surveying at fine resolution will provide detailed insight into changes in both abundance and distribution.

DISCUSSION

The spatial scales at which data on alien plant invasions are assessed clearly affect the perceptions and insights that can be gleaned (Wiens, 1989). The grain (cell size) also substantially alters the overall perceived level of invasion across an area. For example, we show the southern KNP to be highly invaded when assessed at a quaternary-watershed level, while the 0.1×0.1 km scale reveals a much finer pattern to the invasion.

Both quarter-degree grids and tertiary watersheds give a distorted assessment of invasion levels when used at the extent of the whole KNP. However, when considered nationally (e.g. Nel *et al.*, 2004; Rouget *et al.*, 2004) or regionally (e.g. Foxcroft *et al.*, 2007), these scales are useful in broadly guiding management, and perhap, monitoring activities. The quaternary watershed is probably also useful as a scale at which species lists can be compiled, and used in broad-scale risk and priority assessment. The 0.1×0.1 km and 0.25×0.25 km scales are most useful for ecological studies, and where the overall extent is limited, for example, a small nature reserve, this scale is probably appropriate for planning management interventions and monitoring programmes. However, as Barnett *et al.* (2007) point out, the real benefit of mapping will only be realized when combined with plot-based techniques; this is currently being explored in KNP.

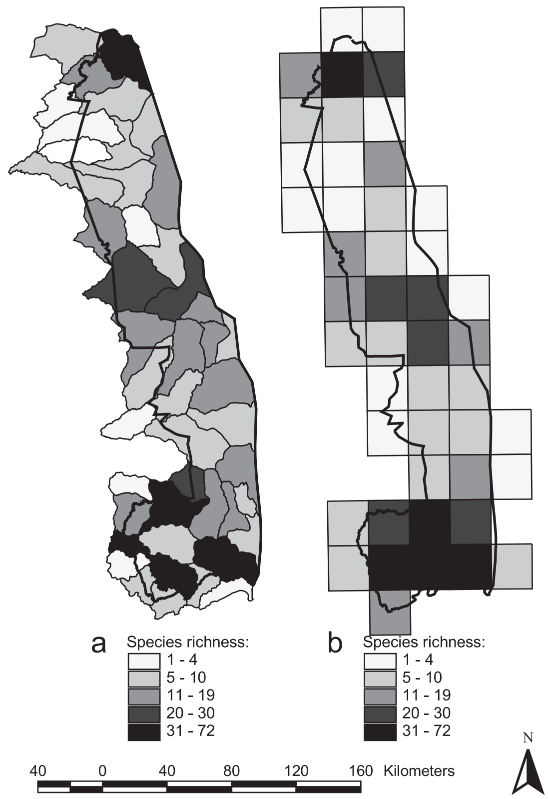

Figure 6 Alien plant richness data for the Kruger National Park, at (a) the quaternary-watershed scale, and (b) the quarter-degree cell scale.

Up-scaling diffuses abundance and distribution patterns, resulting in scattered patchy distribution patterns being depicted as continuous blocks of invaded areas. Similarly, even at fine scales, cells with a single record have the same effect. However, having data available at a fine resolution (point data) allows up-scaling (Pyšek & Hulme, 2005), which, although one looses some detail, may be useful when comparing with other data collected at a coarser resolution (for example via remote sensing; Edwards *et al*., 2002).

Although there was a difference in the effort placed in mapping specific species, assessing the distribution of the most abundant species provides interesting insights. For example, when assessed at a fine scale, the distribution of *Opuntia stricta* can be clearly related to the Skukuza village, allowing for informative reconstruction of the invasion trajectory (Foxcroft *et al*., 2004). *Parthenium hysterophorus* is clearly associated with roads at a fine scale, but the strength of this association, which is crucial for understanding and managing these invasions, is lost at coarser scales. The close association between the distribution of *Lantana camara* and the location of rivers in KNP is another example.

An additional strength of the CyberTracker data set is the large number of records that may be used as absence data or null records in assessing and modelling plant invasions. Although a number of techniques are being developed to use presence-only data for predictive distribution modelling (Robertson *et al*., 2004 and references therein, Tsoar *et al*., 2007), methods using absence

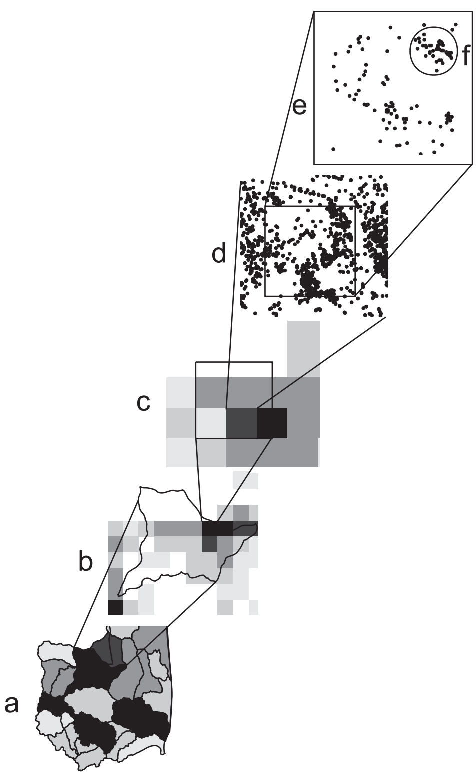

Figure 7 Alien plant richness data from Kruger National Park. The letters at each scale of resolution cross-reference to Table 3. The dots in (d) and (e) are individual alien plant records.

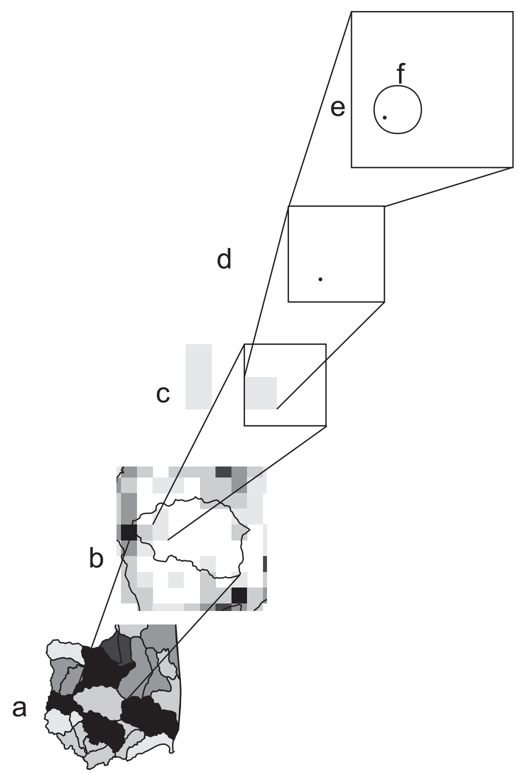

Figure 8 Alien plant data from the Kruger National Park. The dots in (d) and (e) are individual alien plant records.

Table 3 Perspectives gained from alien plant distribution data from the Kruger National Park (KNP) at different spatial scales. The implications indicated are cross-referenced to the levels of resolution in Fig. 7. We discuss the contrast between the high species rich scenario (in this table), to a low species rich scenario (Fig. 8), in the text. QW – quaternary watershed (see Table 2).

Level	Extent	Resolution and data	Pattern and observation	Monitoring implications	Management implications
a	Southern KNP	Species richness per QW	Insight into broad patterns of invasion over a large area. Overestimates the actual extent of invasion, for example (a) appears highly invaded	Useful for determining current and potential species distribution over a wider landscape (e.g. Foxcroft *et al*., 2007)	Broadly directs management interventions (definition of management zones); probably best used at the scale of an entire river course or watershed
b	One QW	Species richness at the 5 × 5 km scale	Even by using relatively large cells (25 km^2) in the QW, species richness ranges widely from zero to high species richness	At this scale the resolution is still too coarse to detect new foci or local increases in abundance	Provides some insight into distribution patterns across a QW, but is still too coarse for use in management plans
c	One 5 × 5 km cell	Species richness at the 2 × 2 km scale	Although some level of detail can be determined at this scale, isolated patches or single plants are aggregated to a large area; perspective of the spatial structure of the invading population is lost	Similar to above	May broadly direct management, although more detailed units (next level down) will be needed for specific management units
d	One 2 × 2 km cell	Actual alien plant distribution	Good insight into the extent of the invasion pattern starts emerging	Species records and abundance assigned to cells at this scale may be useful for repeated surveys to detect changes in range and abundance of alien plants	The 2 × 2 km scale shows site specific details that may be useful for setting contracts for management teams
e	A random selection of points in a cell of 1 × 1 km	A sample of plant distribution points at a finer scale	At this scale, and (f) below, the true nature of the invasion and spatial structure is revealed. Have the plants had the opportunity to sample the entire cell and the current sites are preferred, or is the invasion still expanding?	Useful for the identification of nascent foci	Identification and demarcation of nascent foci is critical for effective management
f	A random selection of points in a radius of < 250 m	Patchiness and distribution of a small cluster of alien plants	At these scale, including (e) above, insights into the spread dynamics and ecology of the species may be determined	In a small region, mapping of individual points or patches will facilitate detailed monitoring of range expansion, increases in abundance and efficacy of management interventions	Probably only useful for management in a small, well demarcated area, where individual plants and patches can be targeted for control

points appear to be more accurate than those using presence-only data (Elith *et al*., 2006). Thus, the large number of absence points is a distinct advantage and facilitates accurate niche-based modelling, providing opportunities for accurately defining potential distributions.

We recommend that the KNP should continue with the collection of data using the CyberTracker programme and that this system should be expanded to other protected areas. Innovative measures are, however, needed to facilitate the collection of data on species that are currently underrepresented. These may include training on species identification, the use of image-driven keys, and area- or species-specific prompts in the CyberTracker programme. Accurate absence data, such as provided by the CyberTracker data set, opens the door for advanced distribution modelling, and also provides a measure of the evenness of sampling. This is important for detecting small populations that have spread far from a source; the chances of finding such nascent foci are increased if an area is evenly sampled.

Furthermore, effective management of plant invasions demands accurate spatial data on the overall distribution within an area, patterns of presence/absence and abundance across the area and co-occurrence with other invasive species, as such information is crucial for planning management interventions, setting realistic targets and monitoring the success of control operations.

ACKNOWLEDGEMENTS

We acknowledge the DST-NRF Centre of Excellence for Invasion Biology and the Hans Sigrist Foundation for funding, and thank M.P. Robertson and three anonymous reviewers for helpful comments on the manuscript.

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Editor: Petr Pyšek