A preliminary assessment of the presence and distribution of invasive and potentially invasive alien plant species in Laikipia County, Kenya, a biodiversity hotspot

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This is the first assessment of naturalised, invasive and potentially invasive alien plant species present in Laikipia County, Kenya, which hosts the highest populations of endangered large mammals in the country. We undertook broad-scale roadside surveys in Laikipia, recording all naturalised and invasive species, and based on an extensive literature review, also compiled a list of those alien species present that are known to threaten biodiversity and livelihoods elsewhere in the world. The data were supplemented by CLIMEX eco-climatic niche models of nine species that we consider to pose the biggest threat to conservation initiatives in the East African region. Of the 145 alien plant species recorded, 67 and 37 (including four species of uncertain origin) were considered to be already naturalised or invasive, respectively, and a further 41 species had been recorded as being naturalised or invasive outside of Laikipia. Most (141) of these species were introduced as ornamentals only or had uses in addition to being ornamentals, with the majority (77) having their origins in tropical America. Widespread species in the county included *Opuntia stricta*, *O. ficus-indica*, *Austrocylindropuntia subulata* and other succulents. Based on the current eco-climatic conditions, most of Laikipia is unsuitable for *Chromolaena odorata*, marginally suitable for *Mimosa pigra* and *Lantana camara*, and a better climatic match, ranked from least to most favourable, for *Tithonia diversifolia*, *Cryptostegia grandiflora*, *Parthenium hysterophorus*, *Prosopis juliflora*, *O. stricta* and *Parkinsonia aculeata*.

Conservation implications: Invasive alien plants are known to have negative impacts on biodiversity, and as such pose significant threats to protected area ecosystems worldwide. Without efforts to eradicate, contain or control invasive plant species in Laikipia, one of the most important conservation areas in eastern Africa many rare and iconic wildlife species may be lost.

Keywords: invasive alien plants; distribution; management; protected areas; alien plant species.

Introduction

Invasive alien species are those plants and animals that have been introduced by people, either intentionally or unintentionally, outside of their natural range or outside of their natural dispersal potential, and are destructive to the environment in which they have established and proliferated (UNEP 2002; Witt & Luke 2017). Invasive alien species (plants and animals) pose a significant threat to biodiversity (Pyšek et al. 2012; Randall 1996; Vilà et al. 2011). For example, a global meta-analysis by Vilà et al. (2011) found that invasive plants decrease native plant species diversity and abundance. These plant invasions may have cascading trophic effects (Bailey, Schweitzer & Whitham 2001; Sakai et al. 2001; Valentine, Roberts & Schwartzkopf 2007) by decreasing animal fitness and abundance (Vilà et al. 2011). This is especially an issue for protected areas where the primary goal is biodiversity conservation (eds. Foxcroft et al. 2013; Funk & Vitousek 2007; Hobbs & Humphries 1995).

De Poorter (2007) identified 487 protected areas worldwide in which invasive alien species (plants and animals) were recorded as a threat. Allen, Brown and Stohlgren (2009) reported 20 305 alien plant species invasions in 218 national parks in the United States. Invasive plant species have also been reported from protected areas in Australia (Setterfield et al. 2013), South America (Pauchard et al. 2013), Europe (Pyšek et al. 2013), India (Hiremath & Sundaram 2013)

Note: Additional supporting information may be found in the online version of this article as Online Appendix 1 and elsewhere (see eds. Foxcroft et al. 2013). More than 60% of managers in United States national parks indicated that alien plant invasions were of moderate or major concern (Randall 2011). Goodman (2003) found that invasive plants pose the biggest threat to protected areas in the province of Kwazulu-Natal, South Africa, and protected area managers in Europe perceive invasive species as the second greatest threat to biodiversity (Pyšek et al. 2013). Invasions also impact on communities that are dependent on natural resources for their survival as reported by Mwangi and Swallow (2008), Maundu et al. (2009), Kebede and Coppock (2015), Shackleton et al. (2017a, 2017b, 2017c) and Witt, Beale and Van Wilgen (2018). There is therefore a global imperative to manage these species to protect biodiversity and improve livelihoods, especially in mixed-use landscapes, where the main goals are biodiversity conservation and livestock production.

Most plant species that are now invasive in protected areas were initially intentionally introduced for ornamental purposes, accidentally by tourists or staff, whereas others may have invaded the protected area through natural dispersal from surrounding areas (Allen et al. 2009; Meyerson & Pyšek 2013). Tourist facilities, including staff villages, and villages interspersed within conservation areas can be an important source of invasive alien plant species. Foxcroft, Richardson and Wilson (2008) surveyed 36 tourist camps and staff villages in the Kruger National Park (KNP), South Africa, and identified 258 alien plant species, several of which had already escaped cultivation and become invasive. In the Garden Route National Park (GRNP), also in South Africa, Baard and Kraaij (2014) recorded 244 species of alien plants of which 59% were invasive. Witt et al. (2017) recorded 245 alien plant species in the Serengeti-Mara ecosystem, East Africa, of which 212 were intentionally introduced into gardens. Of these 212 species, 23 had escaped cultivation, and were recorded as being invasive outside of gardens.

The first step in facilitating the management of these invasive alien plants is to gain a better understanding of their presence, distribution and impacts (Shackleton et al. 2017a, 2017b, 2017c; Witt et al. (2018). Here, we report on the naturalised, invasive and potentially invasive alien plant species in Laikipia County, Kenya, one of the most important multiple-use conservation areas in eastern Africa (Sundaresan & Riginos 2010). Despite only 2% of the land in Laikipia having been set aside exclusively for wildlife conservation (Georgiadis et al. 2007), the county is home to the second highest abundance of wildlife in East Africa, after the Mara-Serengeti ecosystem, and hosts the highest populations of endangered large mammals in Kenya, including half of the country's rhino population, together with significant populations of elephants, Grevy's zebra, reticulated giraffe and wild dogs (Sundaresan & Riginos 2010). In fact, the county is home to a higher diversity of large mammals than either the Serengeti National Park in Tanzania or KNP in South Africa (Sundaresan & Riginos 2010), with the highest diversity of large mammal species of similar size anywhere in the world (Butynski & De Jong 2014). Of the 62 large mammal species present in the county, one is 'critically endangered', two are 'endangered', four are 'vulnerable' and six are 'near threatened' (Butynski & De Jong 2014). Moreover, 50% of Kenya's bird species (i.e. more than 560 species) have been recorded in Laikipia (Butynski & De Jong 2014). The only known previous study on the naturalised and invasive plants present in this county was a field guide produced by Witt (2017), which did not include any detailed analyses of the data collected. Other studies on invasive plants conducted in the area focussed on the invasion of *Opuntia stricta* (Haw.) Haw. (Cactaceae) (Strum, Stirling & Mutunga 2015) or the associated impacts of *O. stricta* invasion (Dudenhoeffer & Hodge 2018; Dyck 2017). We provide a list of naturalised and/or invasive alien plant species recorded in Laikipia and include alien plant species present that are known to be naturalised or invasive elsewhere in the world, but have not been recorded as such in Laikipia at the time of the survey. We also provide distribution data, based on roadside surveys, for the most invasive species. We also assess the eco-climatic suitability of Laikipia to invasions by some of the worst invasive alien plant species in eastern Africa, a few of which are already present in Laikipia. This information will be useful in prioritising species for management to protect biodiversity and enhance livelihoods.

Methods

Study site

Approximately 9500 km^2 in extent, Laikipia County in central Kenya is a mix of grasslands, savanna woodland and forest, lying between the Aberdares Range (4000 m asl) to the south and southwest, Mount Kenya (5200 m asl) to the east and southeast, Eastern (Gregory) Rift Valley (c. 970 m asl) to the west, Karisia Hills (2580 m asl) to the northwest, Mathews Range (2688 m asl) to the north and Buffalo Springs National Reserve and Samburu National Reserve (c. 900 m asl) to the northeast (Butynski & De Jong 2014; Figure 1).

Laikipia experiences a dry and cool climate, which is influenced by the presence of Mount Kenya and the Aberdare mountain range. Daily maximum temperatures are around 25 °C, except for the northern part, which is a little warmer, with December and January being the warmest months (LWF 2012). Mean annual rainfall increases with elevation, from 400 mm in the northeast to 1000 mm in the southwest on the slopes of Mount Kenya and the Aberdares (LWF 2012). There are two main rainy seasons with the 'long rains' falling from March to May, with April being the wettest month, followed by the 'short rains' in November. This range of temperatures and rainfall provides habitats for a large number of native and introduced plant and animal species.

Laikipia is in a transition zone for three major vegetation types: 'Somalia-Masai Semi-desert Grassland and Shrubland', 'Somalia-Masai Acacia-Commiphora Bushland and Thicket' and 'Afromontane Undifferentiated Montane Vegetation'

FIGURE 1: Map showing the location of Kenya in Africa (inset) and the location of Laikipia County within Kenya.

(Butynski & De Jong 2014). This diversity of vegetation types accounts in part, for the high biological diversity of Laikipia.

Land uses in the county include: (1) mix of ranching (livestock farming) and wildlife conservation, which is the most dominant land use, followed by (2) pastoralism and wildlife, (3) cultivation, (4) pastoralism and cultivation, (5) forests, (6) wildlife ranching and (7) urban settlements (LWF 2012). The county is a unique combination of large-scale ranches that make up about 40% of the landscape, with the remainder consisting mainly of community-owned lands. The large-scale ranches focus mainly on wildlife conservation, tourism and raising beef cattle, while the communities are mainly pastoralists. In fact, more than 80% of people in Laikipia are dependent on livestock (Butynski & De Jong 2014).

Species surveys

We recorded all alien plant species during roadside surveys similar to those undertaken by Henderson (2007), Rejmánek et al. (2017), Shackleton et al. (2017a, 2017b, 2017c), Witt and Luke (2017) and Witt et al. (2018) over 2 years from 2014 to 2015. Driving on all accessible roads, including jeep tracks, we recorded the location (using a handheld global positioning system device) and status (present, naturalised and/or invasive), of all alien species that are also known to be naturalised or invasive elsewhere (outside of Laikipia County), based on a review of global databases (CABI 2019; ISSG 2015), and other sources (Witt & Luke 2017; Witt et al. 2018). Alien species were recorded as naturalised if they reproduced consistently, and had established self-sustaining populations that had not yet spread widely, whereas invasive species are those that produce large numbers of reproductive offspring that have spread over substantial distances (Blackburn et al. 2011; Richardson et al. 2000). Alien species present in lodge or other gardens, in areas where the main land use was conservation, were surveyed on foot. We only recorded those alien species that are known to be transformers with the potential to have a major impact on the structure and functioning of ecosystems. This information, together with data on the species growth form, origin and uses, was largely gleaned from the same sources described above. We did not record any alien ruderal or agricultural weeds that are not considered to have a significant impact on biodiversity or rangeland productivity. No surveys of alien species were undertaken in towns because it was logistically too complex to survey a large number of gardens when most home owners were not present during the day.

A new locality for any particular species was only recorded if it was seen at least 1 km from the previous record. In situations where a species could not be immediately identified, specimens were collected or photographed for later identification by specialists. Naturalised and invasive grass species were not recorded, whereas *Morus*, *Bougainvillea* and *Eucalyptus* species were only recorded to genus level because of difficulties in identifying individual species within these genera; they were included in the analysis as 'species'. Vines and many herbaceous plant species are often difficult to observe in the field, especially when not in flower and as such, may have been under-recorded or in some cases not recorded at all. So the absence of a record in a particular area does not mean that the species is not present, just that it was not seen during our surveys.

Locality data acquired through surveys were entered into a database, and distributions were then mapped at 1/16 degree grid cells (~11 km × 11 km) for the most widespread and abundant invasive alien plant species, based on the number of grid cells in which the species was recorded. If a plant species was found to be present, naturalised and invasive at various localities in the same cell, then the latter took precedence in the species map, indicating that it was found to be invasive in at least one locality within that particular cell.

Eco-climatic suitability and impacts of selected species

There are numerous invasive and potentially invasive plant species already present in Laikipia (Witt 2017). In addition, there are a number of problematic species that are abundant and widespread outside of Laikipia, which could potentially invade the county (Witt & Luke 2017). We adapted only published eco-climatic suitability models or developed new models for those species currently present in Laikipia, or absent yet present in the eastern African region, which pose disproportionate threats to biodiversity and rangeland productivity. These are aggressive invaders that are known to displace valuable forage species, reducing carrying capacities of wildlife and livestock, and ultimately impacting on the welfare of communities. The species of most concern in the eastern African region are *Prosopis juliflora* (Sw.) DC (Fabaceae), *Lantana camara* L. (Verbenaceae), *Tithonia diversifolia* (Hemsl.) Gray (Asteraceae), *Parthenium hysterophorus* L. (Asteraceae), *O. stricta*, *Chromolaena odorata* (L.) R.M. King & H. Rob (Asteraceae), *Mimosa pigra* L. (Fabaceae), *Parkinsonia aculeata* L. (Fabaceae) and *Cryptostegia grandiflora* Roxb. Ex R. Br (Asclepiadaceae) (Witt & Luke 2017; Witt et al. 2018). Although some of these species such as *L. camara*, *T. diversifolia*, *P. hysterophorus* (one grid cell) and *O. stricta* are already present in Laikipia, the others have not been recorded there yet. To estimate whether climatic conditions in Laikipia will support further invasions of species already present in the county, and those that are currently absent, yet present in the region, CLIMEX eco-climatic models (Kriticos & Randall 2001) were applied for *C. odorata* (Kriticos et al. 2005), *P. hysterophorus* (Kriticos et al. 2015), *L. camara* (Taylor et al. 2012), *M. pigra* (Walden et al. 2002), *P. aculeata* (Van Klinken et al. 2009) or developed *de novo* for *O. stricta* (D.J. Kriticos unpublished data), *P. juliflora* (D.J. Kriticos unpublished data) and *T. diversifolia* (J.M. Kriticos unpublished data). CLIMEX is used to fit eco-climatic niche models to estimate the potential distribution or phenology of organisms based on distribution data for the target organism, and additional information about the response of the organism to weather variables drawn from experiments or phenological observations (Kriticos et al. 2015; Sutherst & Maywald 1985). The resulting models can then be applied to climatic data to explore the climatic suitability of new regions, in this case East Africa, and more specifically Laikipia County. The distribution data used in the unpublished models were obtained from the Global Biodiversity Information Facility (GBIF) and Witt and Luke (2017). Specific sources of locality data are described in the relevant model publications (Kriticos et al. 2005, 2015; Taylor et al. 2012; Van Klinken et al. 2009; Walden et al. 2002).

We became aware that the known distribution of *C. grandiflora* in South Africa exceeded its niche as modelled using CLIMEX. Therefore, the published model of *C. grandiflora* was modified to fit distribution data from the South Africa Plant Invaders Atlas (SAPIA) database (Henderson & Wilson 2017), which had been acquired subsequent to the development of the original model developed by Kriticos et al. (2003). The only parameter that needed adjustment was the Minimum Annual Heat Sum for Reproduction (PDD), which was reduced to 1200 °C days, allowing the model results to agree with the distribution data.

Ethical consideration

This article followed all ethical standards for a research without direct contact with human or animal subjects.

Results

Species surveys

Almost 50% of the grid cells in Laikipia were surveyed to some extent (Figure 2). It was not possible, because of logistic and other reasons, to survey every single garden, even in areas where the predominant land use was conservation.

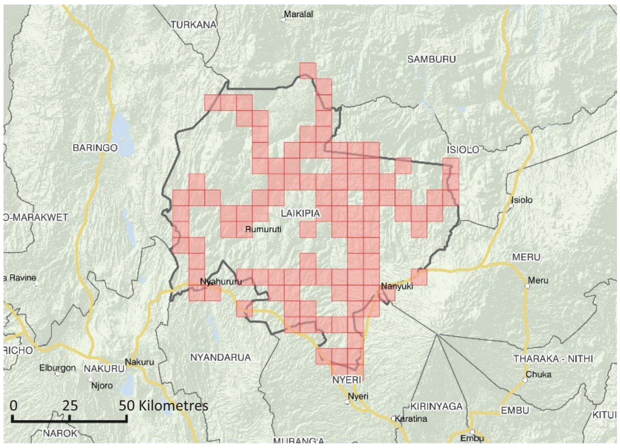

FIGURE 2: Map showing the areas surveyed in Laikipia County, Kenya (surveyed area shown in 1/16 degree grid squares; ~ 11 km × 11 km).

One-hundred and forty-five alien plant species were seen and recorded during our surveys (Online Appendix 1). This includes *Calotropis procera* (Aiton) Dryand. (Apocynaceae), *Ipomoea cairica* (L.) Sweet (Convolvulaceae), *Ricinus communis* L. (Euphorbiaceae), *Senna didymobotrya* (Fresen.) H.S. Irwin & Barneby (Fabaceae) and *Solanum campylacanthum* A. Rich (Solanaceae), which have an uncertain origin, although considered by some to be native to eastern Africa (See Witt 2017; Witt & Luke 2017). They were considered to be naturalised and/or invasive in our analysis. There was also uncertainty as to the identification of *Vinca major* L. (Apocynaceae), *Azolla filiculoides* Lam. (Azollaceae) and *Crocosmia x crocosmiiflora* (Lemoine) N.E.Br. (Iridaceae), but these were nevertheless also included as such in the analysis. This uncertainty occurred because *V. major* and *V. minor* L. are morphologically very similar to each other, whereas *A. filiculoides* could be confused with *A. cristata* Kaulf. (Salviniaceae), which is more common in tropical regions, or the native *A. pinnata* subsp. *africana* (Desv.) Saunders and Fowler. Both *Argemone mexicana* L. and *A. ochroleuca* Sweet were recorded as a single taxon.

Most of the alien species recorded were in the families Fabaceae (16 species), Asteraceae (12), Crassulaceae (11), Cactaceae (10) and Solanaceae (8). Of the 145 alien plant species recorded, 67 were considered to be naturalised in Laikipia, although there was uncertainty with regard to the invasion status of *Cosmos bipinnatus* Cav. (Asterceae), which was included as naturalised for the purposes of this study. Most naturalised species recorded belonged to the families Cactaceae (nine species), Crassulaceae (nine), Asteraceae (eight), Fabaceae (six) and Solanaceae (five). Thirty-seven species were regarded as being invasive in Laikipia, belonging mainly to the Asteraceae (six species), followed by five species in each of Fabaceae and Solanaceae, and four in each of Crassulaceae and Cactaceae.

The dominant growth forms of all alien species in Laikipia considered to be naturalised, invasive or potentially invasive included trees or shrubs (59 species), followed by herbs (31) and climbers (16) (Table 1). Naturalised species were

TABLE 1: Growth forms of alien species seen in Laikipia County, Kenya, considered to be naturalised, invasive or potentially invasive.

Growth form	All aliens	Naturalised	Invasive
Woody tree or shrub	59	19	10
Herb	31	20	13
Climber	16	3	2
Succulent herb	16	9	4
Succulent tree or shrub	14	13	7
Aquatic	4	2	1
Woody tree or shrub or climber	4	1	0
Fern	1	0	0

TABLE 2: Uses of alien species seen in Laikipia County, Kenya, considered to be naturalised, invasive or potentially invasive.

Use	All aliens	Naturalised	Invasive
Ornament	142	60	32
Barrier	54	29	11
Agriculture	27	14	9
Medicinal	17	7	7
Domestic	16	6	3
Silviculture	5	4	2
Cover or binder	3	0	0
None	2	3	2

dominated by herbs (20 species) and trees or shrubs (19), with invasive plants following a similar pattern. Most of these alien species were intentionally introduced as ornamentals, although some ornamentals were also used for other purposes (Table 2). Most of the naturalised and invasive plant species were used, among others, for ornamental, barrier or agricultural purposes. The majority of naturalised species (27) were only used for ornamental purposes, and 14 of the invasive plant species had no other uses other than ornamental. The vast majority of aliens included in this study originated from tropical America (74), followed by species from temperate Africa (17) and Madagascar (11), and most of those considered to be naturalised and invasive also had a tropical American origin (Table 3).

Distribution

Opuntia ficus-indica was seen (recorded as present) in 43% of the grid cells surveyed, followed by *Austrocylindropuntia subulata* (41%), *Datura stramonium* L. (Solanaceae) (38%), *Agave sisalana* (37%), *O. stricta* (31%) and *Agave americana* (30%). *Opuntia ficus-indica* was the most widely naturalised species, followed by *A. americana*, *A. subulata*, *A. sisalana* and *O. stricta*. *Datura stramonium* L. (Solanaceae) was the most widespread invasive plant species seen, recorded as such in 28 of the 111 grid cells surveyed, followed by *O. stricta* (19), *O. ficus-indica* (18), *Cirsium vulgare* (Savi) Ten. (Asteraceae) (14), *A. subulata* (11), *Xanthium strumarium* L. (Asteraceae) (9), *Bryophyllum delagoense* (Eckl. & Zeyh.) Schinz (Crassulaceae) (9), *Verbena bonariensis* L. (Verbenaceae) (6) and *Acacia mearnsii* De Wild. (Fabaceae) (5) (Figure 3). *Datura stramonium* was scattered and widespread throughout Laikipia, present wherever there was significant disturbance, especially along roadsides, whereas most other invasive plant species had a clumped distribution. Although species such as *B. delagoense* and *O. engelmannii*

TABLE 3: Regions of origin of species seen in Laikipia County, Kenya, considered to be naturalised, invasive or potentially invasive.

Origin	Numbers	Naturalised	Invasive
Africa – Temperate	17	7	3
Africa – Tropical	6	5	4
America – Temperate	5	3	3
America – Tropical	74	35	21
Asia – Temperate	7	0	0
Asia – Tropical	5	2	1
Australia/Asia – Tropical	3	0	0
Australia – Temperate	8	4	2
Australia – Tropical	2	1	0
Eurasia	3	1	1
Madagascar	11	7	3
Mediterranean	3	1	0
Oceania	1	0	0

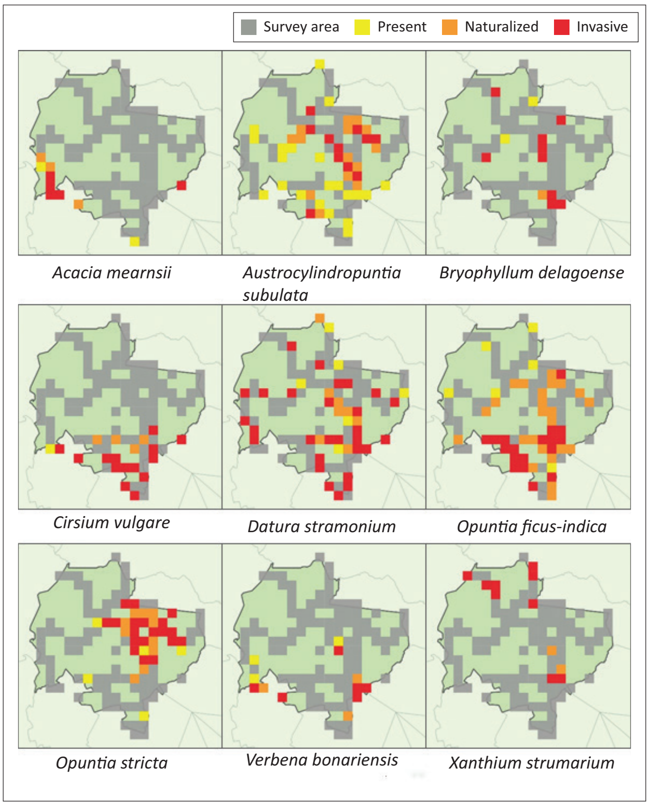

FIGURE 3: Maps showing the distribution of nine of the most widespread invasive plant species in Laikipia County, Kenya.

(Salm-Dyck ex Engelm. (Cactaceae) were not widespread in Laikipia, they were invasive in 75% or more of the grid cells in which they were recorded. Invasive species such as *Pistia stratiotes* L. (Araceae), *P. aculeata*, *P. juliflora*, *C. grandiflora*, *M. pigra* and *Passiflora subpeltata* Ortega (Passifloraceae), which are widespread elsewhere in Kenya and/or eastern Africa, were not seen in Laikipia during surveys.

Eco-climatic modelling

The CLIMEX eco-climatic niche models indicate that much of Laikipia is climatically very suitable for further invasions by *O. stricta* (Figure 4). Climatic conditions may also favour the establishment and proliferation of

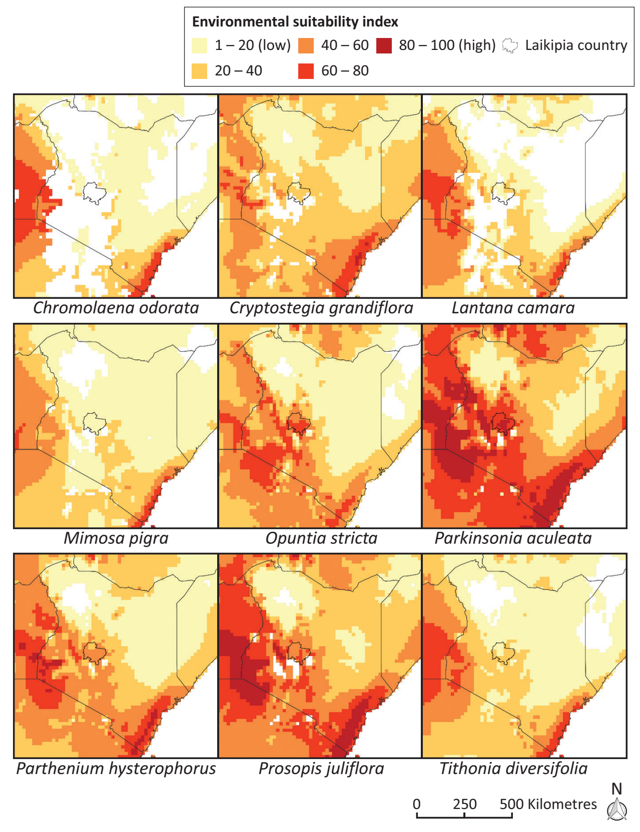

FIGURE 4: The eco-climatic suitability of Laikipia County, Kenya, for nine plant species known to be invasive in eastern Africa based on CLIMEX eco-climatic niche models. Shading depicts the eco-climatic indices (suitability of each location); the darker the shading, the more suitable the climate in that area is for these species to establish and proliferate.

P. aculeata and *P. juliflora*, and *P. hysterophorus* is likely to establish and spread throughout most of Laikipia. However, we postulate that it is unlikely to be as problematic as in other areas in eastern Africa that are more climatically suitable (e.g. south-western and southern Kenya). The present climate in Laikipia does not appear to be suitable for *C. odorata*, although *L. camara* may expand its current distribution but is unlikely to proliferate (Figure 4). Climatic conditions are suitable for *C. grandiflora* and *T. diversifolia.* With no extensive floodplains or swamps, *M. pigra* is unlikely to invade in Lakipia, although plants may establish along some water bodies.

Discussion

The presence of a large number of alien species, mainly ornamentals, a range of climatic regimes (LWF 2012), vegetation types (Butynski & De Jong 2014) and land-use practices ranging from crop production to conservation (LWF 2012) increase the risk of plant invasions (Catford, Jansson & Nilsson 2009; Saunders, Hobbs & Margules 1991) across the Laikipia landscape. Data from protected areas in South Africa support this assertion (Baard & Kraaij 2014; eds. Foxcroft et al. 2017). The GRNP and Table Mountain National Park, both in South Africa, are similar in some respects in that they are both fragmented, and nestled among a range of different land-use types, with comparable numbers of alien plant species (Baard & Kraaij 2014). The GRNP consists of approximately 30 detached portions, with farmland, plantations and towns dispersed along its boundaries, making it highly susceptible to invasions (Baard & Kraaij 2014). Of the 244 species of alien plants recorded outside of gardens in the GRNP, 23 were casual aliens, 66 were naturalised, 144 were invasive and 12 were transformers (Baard & Kraaij 2014). These figures are comparable to those of Table Mountain NP (Baard & Kraaij 2014). The only national park in South Africa which has more plant species listed as invasive, based on the *National Environmental Management: Biodiversity Act* (NEM:BA) than either the GRNP (98 species) or Table Mountain NP (114), is the considerably larger KNP with 130 species (Baard & Kraaij 2014; eds. Van Wilgen & Herbst 2017). However, 96 species recorded as invasive in GRNP are not listed by NEM:BA as requiring regulation (Baard & Kraaij 2014), which supports the contention that fragmented conservation areas within mixed-use landscapes may be at higher risk of invasions. There is no similar comparative data for eastern Africa, other than that from the Serengeti-Mara ecosystem, which also consists of multiple land-use types, but has two large contiguous conservation areas, far larger than in Laikipia, in the Serengeti NP and Masai-Mara National Reserve. Witt et al. (2017) recorded 245 alien plant species in this ecosystem, of which 212 were intentionally introduced. Of these 212 species, 23 were invasive (Witt et al. 2017) compared with 67 naturalised and 37 invasive plant species in Laikipia. According to Spear et al. (2013), high human populations and their associated activities, which may include gardening, in areas surrounding protected areas, may be driving these invasions.

Plants in cultivation are often the main source of invasions (Bucharova & Van Kleunen 2009; Hulme et al. 2008, 2014, 2018; Van Kleunen, Bossdorf & Dawson 2018). According to Van Kleunen et al. (2018), at least 75% and 93% of the globalised naturalised alien flora is grown in domestic and botanical gardens, respectively. The substantial *O. stricta* invasion in Kruger NP originated from plants in the staff village in Skukuza (Foxcroft at al. 2004). We also assume that the *O. stricta* invasion in Laikipia reportedly originated from plantings in the Colonial Administrators residence in Doldol (0°24′00.0″N; 37°10′00.0″E), a small town in the east of Laikipia County, although invasions of *O. engelmannii* on Loisaba Conservancy (0°21′38.1″N; 36°46′55.3″E) originated from hedge plants that had been discarded in a quarry from where they subsequently spread.

Many of the *Bryophyllum* and *Crassula* species spreading in Laikipia are cultivated in gardens, largely because they are so well adapted to local conditions. The escape and subsequent establishment of *Cereus jamacaru* DC. (Cactaceae) on Ol Jogi Conservancy (0°18′54.78″N; 36°58′32.15″E) in Laikipia can also be directly linked to plants grown in lodge gardens on the property (Witt 2017; Witt & Luke 2017). *Austrocylindropuntia subulata* has escaped cultivation and has established widely, mainly along water channels (Witt 2017; Witt & Luke 2017). Despite being invasive, it is still actively being planted as a hedge, and in some cases, even used on earthen dam walls on conservancies to prevent elephant damage (A.B.R. Witt pers. observ.).

The threat of naturalised, invasive and potentially invasive succulent species, with the exception of *O. stricta* and *O. engelmannii*, is largely being ignored in Laikipia, despite their known negative impacts (Witt 2017; Witt & Luke 2017). For example, similar to other invasive cactus species, *C. jamacaru* can form dense stands, displacing native plants and preventing access to forage by grazers and browsers, resulting in reduced livestock- and/or wildlife-carrying capacities. Thickets may also impede the movement of livestock and wildlife, and the spines may cause injuries to people and animals (see Witt 2017; Witt & Luke 2017). Other potentially invasive cacti, such as *Cylindropuntia imbricata* (Haw.) Knuth (Cactaceae) and *Opuntia microdasys* (Lehm.) Pfeiff., are also present in the town of Doldol. According to ISSA (2016), the spiny cladodes of *C. imbricata* adhere to 'passing animals and the barbed spines can penetrate their skin and feet causing severe injuries' (n.p.). The succulent herb *B. delagoense* is another aggressive invader that is expanding its range rapidly in Laikipia. It is allelopathic, so it can readily displace grasses and legumes, forming dense monotypic stands (Groner 1975). It is also highly toxic (McKenzie & Armstrong 1986). In 1997, 125 head of cattle died after eating this species on a travelling stock reserve near Moree in New South Wales, Australia (McKenzie, Franke & Dunster 1987). No activities are being undertaken to manage any of these invasive and potentially invasive plant species.

Appropriate management responses

Alien plant invasions pose significant threats to conservation and livelihoods in Laikipia County (Shackleton et al. 2017c; Witt 2017; Witt & Luke 2017). As such, it would be prudent to develop and implement management strategies to reduce the threats of all invasive and potentially invasive plant species. To that end, it is imperative that all naturalised, invasive and potentially invasive alien plant species be removed from the grounds of all tourist facilities and possibly also villages that fall within areas where the main land-use practice is livestock production and conservation. Those plants that have already escaped cultivation should be eradicated, if possible, or their further spread contained. Finally, biological control solutions for widespread and abundant species should be implemented wherever possible, as has been performed for *O. stricta* and initiated for *O. engelmannii* (Witt et al. 2020).

Many plant invasions in protected areas have originated from tourism facilities and staff villages (Foxcroft & Freitag-Ronaldson 2007; Witt et al. 2017). Although attempts to remove these species may be resisted by many residents (Foxcroft et al. 2008), this opposition could largely be overcome by implementing a more gradual and nuanced approach. For example, strategies implemented in the Kruger NP included the removal of high-risk species first, followed by the removal of low-risk species at a later stage, and the clearing of staff gardens whenever a house was vacated (Foxcroft at al. 2008). Another approach may be to replace alien species with native species, facilitated through the establishment of nurseries focussing on indigenous plantings. Actions can also be supported by undertaking Weed Risk Assessments, or similar, which should ideally include eco-climatic maps to determine the climatic suitability of Laikipia to invasions by selected species (Kriticos, Beautrais & Dodd 2018). Cost–benefit analyses (CBAs) should ideally also be undertaken to consider issues around those species that have benefits but are also known to be invasive – the so-called conflict species such as *Prosopis juliflora* (Wise, Van Wilgen & Le Maitre 2012).

If no scientific evidence is available to support these actions, then the precautionary principle (Principle 15 of the 1992 Rio Declaration) which states that 'where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation' (n.p.) (UN 1992) should be invoked. Finally, there is also legislation, supporting the removal of invasive and even exotic species from protected areas (see Witt et al. 2017). Failure to remove invasive or potentially invasive species will merely increase management costs as they escape cultivation and proliferate (eds. Wittenberg & Cock 2001).

Once alien species have escaped cultivation and established in natural habitats all efforts should be made to eradicate populations, if possible. This can only be achieved if new incursions are detected early and populations are small and localised (eds. Wittenberg & Cock 2001). This requires the establishment of surveillance teams or units that are well versed in the identification of alien plant species. Resources should also be available at short notice to implement any interventions. *Cereus jamacaru* is currently a good target for local eradication because it has only recently escaped cultivation in Laikipia (Witt 2017). If this species is not targeted as a matter of urgency, control costs will increase over time as will the impacts on biodiversity.

For widespread and abundant species, we strongly advocate the use of biological control, if effective agents are available (Day, Witt & Winston 2020; Winston et al. 2014; Witt 2017; eds. Wittenberg & Cock 2001). Reviews have indicated that this is a very safe management intervention (see Hinz, Winston & Schwarzländer 2019). Ideally, biological control should be integrated with other control practices, wherever possible. Biological control is cost-effective, sustainable and environmentally friendly (Day & Witt 2019; Van Wilgen & De Lange 2011; eds. Wittenberg & Cock 2001). There are many additional benefits associated with biological control including the fact that agents establish self-perpetuating populations, often across the whole range of the target species (Greathead 1995). In addition, most biological control projects only require a one-off investment, and benefits can be reaped by many stakeholders independent of their financial status and irrespective of the fact that if they contributed to the initial research (Greathead 1995). The economic returns from biological control projects have also been phenomenal with estimated benefit–cost ratios ranging from 8:1 up to 3726:1 in South Africa (Van Wilgen & De Lange 2011).

Although rarely implemented in Kenya, biological control has widely been used at a global level with 1555 separate and intentional releases of 469 species of biological control agents against 175 invasive plant species across 90 countries (Winston et al. 2014). There are a number of widespread and abundant invasive plant species in Laikipia that could be targeted for biological control (Winston et al. 2014). The cochineal *Dactylopius opuntiae* (Cockerell) 'stricta' biotype (Dactylopiidae), recently introduced for the control of *O. stricta*, is already established in Laikipia (Witt et al. 2020). Species such as *O. ficus-indica* and *O. monacantha* have been brought under good control through the introduction of cochineal in the last century (Winston et al. 2014). Permission is currently being sought from the regulatory authorities to introduce another biotype of *D. opuntiae* for the control of *O. engelmannii*. *Cereus jamacaru* has also been brought under good biological control in South Africa (Zachariades et al. 2017), an option should this species become invasive, although populations are currently such that it can still be eradicated in Laikipia. Although *P. hysterophorus* populations are currently localised, biological control agents could also be introduced (Strathie, McConnachie & Retief 2011), should the species expand its range in Laikipia.

Additional agents are also available for *L. camara* (Urban et al. 2011), and agents were recently released for the control of *T. diversifolia* in South Africa (Simelane, Mawela & Fourie 2011). A number of agents are also available for other alien plants present in Laikipia that could potentially become invasive, provided that they pose no risk to native plants. However, there are a number of targets for which no effective or host-specific agents have been found. For example, despite the sourcing of a number of potential agents for the control of *B. delagoense*, none are suitably host-specific for release in Africa. In this case, concerted efforts will need to be made using conventional means to stop its further spread and reduce the density of current invasions. Intervention strategies will need to be developed and implemented for every species based on the control methodologies available locally and internationally. Failure to manage invasive alien plants in Laikipia will lead to the demise of biodiversity and erode rangeland productivity to the detriment of its people.

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Competing interests

The authors declare that they have no financial or personal relationships that may have inappropriately influenced them in writing this article.

Authors' contributions

A.B.R.W was responsible for undertaking the field surveys, assisted by W.N. who also entered the field data. T.B. undertook the spatial analysis and compiled the maps, and D.J.K. contributed to the development of the CLIMEX niche models. The interpretation of the results and writing of the article was undertaken by A.B.R.W. with inputs from the other authors.

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Data availability statement

Much of the data has been uploaded to the GBIF website - Witt, A.B.R. & Beale, T., 2018, CABI Africa Invasive and Alien Species data. CAB International. Occurrence dataset can be accessed at https://doi.org/10.15468/pkgevu via GBIF.org.

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