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Information for Authors and Readers:

Focus and scope

The journal aims to disseminate, to a wide audience, knowledge, information and innovative approaches that promote and enhance the wise use and management of biodiversity in order to sustain the systems and species that support and benefit the people of Africa.

The journal publishes original research findings, as well as reviews, commentaries or perspectives, strategies and short communications. Special focus issues emanating from symposia or conferences that fall within the scope of the journal may also be published.

Authors should contextualise submissions within the framework of the value chain of biodiversity knowledge from its generation, to its application and use. We are especially interested in articles that are written using language and terminology that is accessible to a wide audience.

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1. Generation of new knowledge that provides a foundation for assessment, planning or management of biodiversity, including new taxonomic discoveries within Africa, from across all Kingdoms of organisms, documenting the abundance, diversity and distribution of genes, species and ecosystems in Africa (including temporal changes in these), and understanding the interactions among components of biodiversity that contribute to the functioning of ecosystems.
2. Assessment of biodiversity, including the status of populations, species and ecosystems, the impacts of threats, harvesting and disturbance or of interventions on populations, species and ecosystems, and the value of the goods and services provided by biodiversity.
3. Innovation in science- or evidence-based decision-making for biodiversity in Africa. This includes the publication of case studies, best practices, tools and plans for the conservation, use and management of biodiversity.
4. Cross-cutting fields specifically developments and innovation in human capital development in the biodiversity sector and innovation in biodiversity information management and dissemination systems and tools for use of biodiversity information.
5. Strategic frameworks that provide guidance and direction for biodiversity research, assessment and management at community, local, national, regional or continental levels, especially those that integrate biodiversity management with local and regional socio-economic systems.

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The editorial team of Bothalia – African Biodiversity & Conservation recognises the value and importance of the peer reviewer in the overall publication process – not only in shaping the individual manuscripts, but also in shaping the credibility and reputation of our journal. We are committed to the timely publication of all original, innovative contributions submitted for publication. As such, the identification and selection of reviewers who have expertise and interest in the topics appropriate to each manuscript are essential elements in ensuring a timely, productive peer review process. We would like to take this opportunity to thank all reviewers who participated in shaping this volume of Bothalia – African Biodiversity & Conservation. We appreciate the time taken to perform your review(s). This list include reviewers of manuscripts that were rejected post-review during 2020.

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Woody vegetation change over more than 30 years in the interior duneveld of the Kalahari Gemsbok National Park

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Background and objectives: Long-term studies of woody plants in South Africa are scarce. This study, initiated in the late 1970s, therefore aids understanding of vegetation dynamics in the southern Kalahari by investigating woody vegetation change at and away from a watering point.

Methods: At three sites, all woody individuals were counted by species in plots 0.5 or 1 ha in size. Seedlings were noted separately from the >0.2 m group of individuals.

Results: *Vachellia erioloba* and shrub density decreased over time whereas dwarf shrub species' numbers fluctuated markedly. Additionally, no increase in density of known bush encroaching species (e.g. *Grewia flava*, *Rhigozum trichotomum* and *Senegalia mellifera*) was found in this large conservation area.

Discussion and conclusion: The changes in density of the woody species seem to point to the importance of particular rainfall patterns or sequences of events over different years that are responsible for these changes in the southern Kalahari, and the evident lack of bush encroachment in this conservation area supports the notion that bush encroachment in arid savannas is driven primarily by land-use practices and not by elevated carbon dioxide levels that are sometimes provided as cause for encroachment.

Key words: bush encroachment, conservation area, Kgalagadi Transfrontier Park, southern Kalahari, *Vachellia erioloba*, vegetation dynamics, watering point.

Introduction

Detecting environmental change at multiple spatial and temporal scales through biotic and abiotic research is of crucial importance not only to policymakers and scientists, but also to natural resource managers (Haase et al. 2018; Parr et al. 2002; Peters et al. 2014). Long-term monitoring can be used as a tool to assess the past management of natural resources, but also provides an understanding of ecological patterns and processes, which can improve decisions on the management of ecosystem assets (Lindenmayer & Likens 2009).

Lindenmayer and Likens (2010) identified three broad, long-term monitoring approaches, these are: (i) curiosity-driven or passive monitoring; (ii) mandated monitoring; and (iii) question-driven monitoring. The first type, passive monitoring, usually has no specific questions or underlying study design and has limited rationale other than curiosity, while the second type, mandated monitoring, is a requirement of government legislation or a political directive. Question-driven monitoring, the third type, generally tests predictions that are guided by a conceptual model and rigorous design. The categories are, however, not mutually exclusive.

There are still relatively few biodiversity time-series that span decades (Magurran et al. 2010) and this is particularly true for woody species (Moustakas et al. 2008). In the southern hemisphere, observational networks and research investment are largely lacking, and therefore even relatively short-term current and archived historical data sets can provide baselines for investigating change (Chambers et al. 2016).

Numerous surveys were initiated in the Kalahari Gemsbok National Park (KGNP) [now part of the Kgalakgadi Transfrontier Park (KTP)] to document vegetation change from 1978 onwards. The aim of this paper is to report on the monitoring that was initiated at three sites after a number of years with above-average rainfall, and follows a passive monitoring approach. The principal questions asked at the time were: how does the woody vegetation change at and away from a watering point, and what is the rate of survival at each of the sites? Although the research was not hypothesis driven (Lindenmayer & Likens 2010), monitoring was conducted over nearly four decades and therefore the data warrant exploration and reporting.

Study area

The study was conducted in the KGNP in South Africa. The KGNP covers about 9 600 km² and is situated between 24°15′ S and 26°30′ S and 20°00′ E, and 20°45′ E in the southwestern corner of the Kalahari region (Van Rooyen et al. 2008). Monitoring was conducted at three sites in the vicinity of the Dankbaar watering point, which was opened in 1959 (Figure S1). The study sites were situated within the *Acacia* (*Vachellia*) *erioloba–Schmidtia kalahariensis* Low Duneveld (Van Rooyen et al. 2008). This open tree savanna occurs in the interior duneveld in the northern part of the park. The vegetation is dominated by *V. erioloba* and *S. kalahariensis* (grass), with other prominent woody species being *Boscia albitrunca, Rhigozum trichotomum* and *Senegalia mellifera*.

Rainfall is received mainly in late summer with a mean of 194 mm/yr recorded from 1976 to 2015 at Nossob Rest Camp (Figure S2). The rainfall is highly erratic (standard deviation ± 88.8 mm) and occurs primarily from January to April, with a peak in March. Temperatures show a large amplitude with winter lows reaching -10.3°C and summer highs reaching 45.4°C (Van Rooyen & Van Rooyen 1998).

Methods

Study sites

Three study sites were established in the interior duneveld between 1978 and 1982. The first site was 5 km to the east of the watering point (25°03′39.13″ S and 20°07′17.37″ E) (hereafter referred to as EoWP) and monitoring commenced in 1978. The second site, at the Dankbaar watering point, (25°04′10.90″ S and 20°05′47.50″ E) (hereafter referred to as WP), was monitored for the first time in 1980. At the third site, 5 km to the north of the watering point, (25°01′39.45″ S and 20°05′0.30″ E) (hereafter referred to as NoWP), monitoring started in 1982. At the time when monitoring commenced, WP was dominated by a dense stand of *V. erioloba* saplings; NoWP had an intermediate density of relatively young *V. erioloba* individuals; whereas EoWP was a mixed stand of mature *V. erioloba* and *Vachellia luederitizii* individuals at a low density. The plots at WP and NoWP were 0.5 ha in size, while the plot EoWP was 1 ha in size. In each plot, all woody individuals were counted by species. Additionally, seedlings (individuals <0.2 m tall) were noted separately from the sapling and mature group of individuals (>0.2 m individuals). All three plots were monitored intermittently, i.e. WP sampled 16 times, NoWP 14 times and EoWP 9 times, including the initial and 2016 surveys.

Statistical analysis

To visualise change in density over time at the different sites, we used linear regressions with the natural log (=ln) density (number of individuals/ha) per species over time (survey years), in the package Graphpad Prism (version 5, graphpad.com). Data for each site were analysed separately. Only species that occurred in the plots on four or more occasions were included in the analyses i.e. a minimum of four data points.

A linear regression of (a) seasonal; (b) annual; or (c) the cumulative annual rainfall of the previous three years against the annual change in tree density between two survey years was investigated.

Results

Generally, the density of tree species declined over the monitored period (Table 1). Furthermore, this decline was significant for *Vachellia erioloba* individuals (>0.2 m) at WP and NoWP (Figure 1a). Additionally, the seedlings (< 0.2 m) of *V. erioloba* decreased significantly at WP (Figure 1b).

For the numerous shrub species counted in the plots during the monitoring period (Table 1), shrub density declined significantly for only three shrub species i.e. *Ehretia alba*, *Lycium bosciifolium* and *Rhigozum trichotomum*. Densities of *E. alba* showed a significant decrease at WP and EoWP (Figure 2a). *Lycium bosciifolium* density decreased significantly at WP (Figure 2b). *Rhigozum trichotomum* density also declined significantly NoWP (Figure 2c).

Table 1: Equations, r^2- and p-values of the polynomial regressions fitted to the density data at three sites (watering point, north of watering point and east of watering point) illustrated in figures 1, 2 and 3. Only species with a minimum of four data points were used in the analyses.

Species	Watering point (WP)	5 km north of watering point (NoWP)	5 km east of watering point (EoWP)
Trees			
Boscia albitrunca	$y = 0.0069x + 17.323$, $r^2 = 0.015$, $p = 0.650$	$y = 0.002x – 3.684$, $r^2 = 0.011$, $p = 0.730$	$y = -1.4E^{-05}x + 3.301$, $r^2 = 1.11E^{-07}$, $p = 0.999$
Vachellia erioloba (sapling/ mature)	$y = -0.040x + 84.232$, $r^2 = 0.383$. $p = 0.011$*	$y = -0.040x + 84.711$, $r^2 = 0.0.907$, $p = 1.52E^{-07}$***	$y = -0.033x + 68.864$, $r^2 = 0.272$, $p = 0.1499$
Vachellia erioloba (seedlings)	$y = -0.377x + 752.291$, $r^2 = 0.617$, $p = 0.021$*	$y = 0.022x – 42.021$, $r^2 = 0.025$, $p = 0.801$	$y = -0.002x + 5.338$, $r^2 = 0.005$, $p = 0.972$
Vachellia haematoxylon	$y = 0x + 0.693$, $r^2 = 1$	$y = 0.017x – 32.452$, $r^2 = 0.137$, $p = 0.293$	-
Vachellia luederitzii (sapling/ mature)	$y = -0.065x + 122.126$, $r^2 = 0.439$, $p = 0.007$	-	$y = -0.020x + 43.232$, $r^2 = 0.679$, $p = 0.006$**
Vachellia luederitzii (seedlings)	-	-	$y = -0.503x + 1000.157$, $r^2 = 0.600$, $p = 0.124$
Shrubs			
Ehretia alba	$y = -0.079x + 159.184$, $r^2 = 0.697$, $p = 0.0001$***	-	$y = -0.030x + 62.889$, $r^2 = 0.0.527$, $p = 0.027$*
Grewia flava	$y = -0.012x + 25.484$, $r^2 = 0.0.018$, $p = 0.633$	-	$y = 0.0167x – 30.388$, $r^2 = 0.118$, $p = 0.406$
Grewia retinervis	$y = 0.065x – 127.501$, $r^2 = 0.206$, $p = 0.365$	-	$y = -0.008x + 18.888$, $r^2 = 0.002$, $p = 0.916$
Lycium bosciifolium	$y = -0.067x + 136.606$, $r^2 = 0.390$, $p = 0.013$*	-	$y = -0.038x + 79.961$, $r^2 = 0.331$, $p = 0.233$
Rhigozum trichotomum	$y = -0.0258x + 55.088$, $r^2 = 0.189$, $p = 0.093$	$y = -0.051x + 104.018$, $r^2 = 0.534$, $p = 0.001$**	$y = -0.019x + 44.091$, $r^2 = 0..398$, $p = 0.093$
Searsia tenuinervis	-	-	$y = 0.028x – 55.349$, $r^2 = 0.397$, $p = 0.130$
Senegalia mellifera (mature)	-	-	$y = -0.010x + 19.963$, $r^2 = 0.091$, $p = 0.429$
Senegalia mellifera (seedlings)	-	-	-
Dwarf shrubs			
Aptosimum albomarginatum	-	-	$y = -0.114x + 232.37$, $r^2 = 0.978$, $p = 0.011$*
Asparagus nelsii	-	$y = -0.028x + 59.187$, $r^2 = 0.378$, $p = 0.019$*	-
Chrysocoma obtusata	$y = 0.091x – 178.253$, $r^2 = 0.376$, $p = 0.059$	-	-
Hermannia burchelli	-	-	-
Hermannia tomentosa	-	-	-
Justicia incana	$y = -0.095x + 193.492$, $r^2 = 0.474$, $p = 0.013$*	-	$y = -0.111x + 227.312$, $r^2 = 0.754$, $p = 0.005$**
Plinthus sericeus	$y = 0.038x + 73.733$, $r^2 = 0.217$, $p = 0.293$	$y = 0.069x – 135.134$, $r^2 = 0.247$, $p = 0.100$	-
Pollichia campestris	$y = -0.034x + 71.169$, $r^2 = 0.190$, $p = 0.119$	$y = -0.038x + 79.328$, $r^2 = 0.395$, $p = 0.016$	-

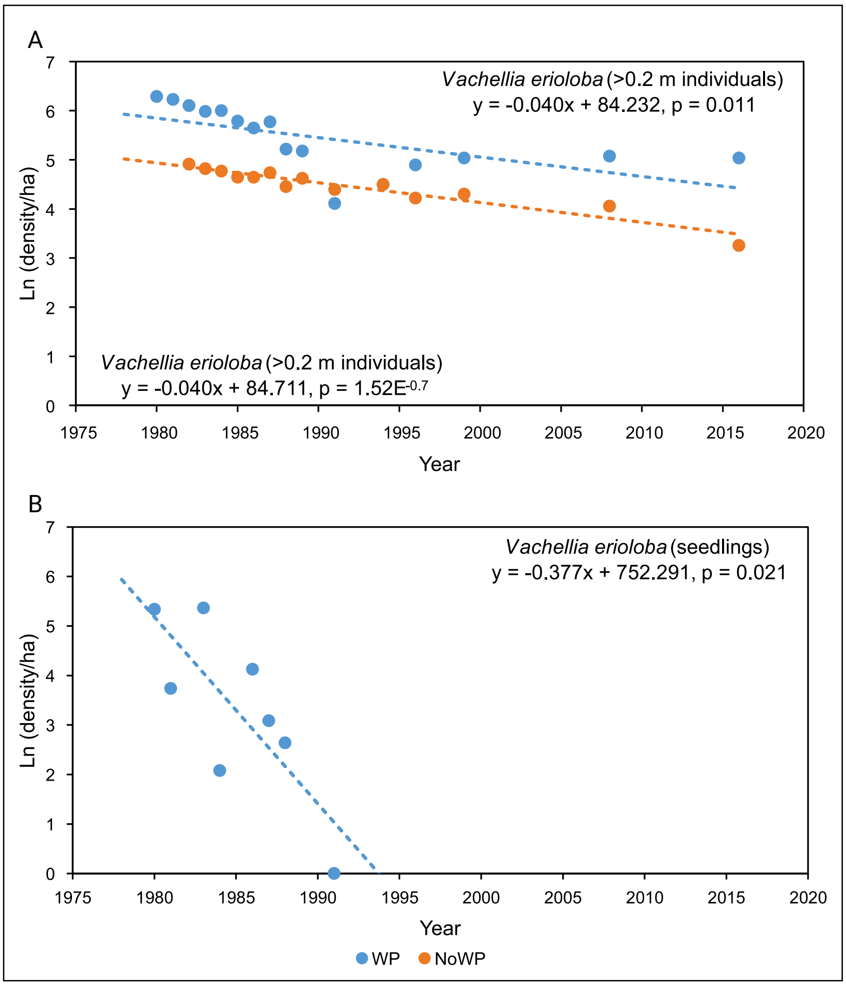

Figure 1. Linear regressions of the natural logarithm of the number of individuals per hectare, indicating significant trends in density of *Vachellia erioloba* over time. (a) >0.2 m individuals, and (b) seedlings. WP = Watering point, NoWP = North of watering point.

Overall, the dwarf shrub species showed large fluctuations in density over the monitored period, with no clear trends evident (Table 1). The density of *Asparagus nelsii* (EoWP), *Aptosimum albomarginatum* (NoWP), *Justicia incana* (WP, EoWP) and *Pollichia campestris* (NoWP) decreased significantly over the monitoring period (Figure 3).

No relationship between tree density and seasonal or annual rainfall or the cumulative annual rainfall of the previous three years was found. This does not exclude rainfall as driving factor, but seems to point towards the effect of a particular rainfall pattern or sequence of events over different years that is responsible for changes in tree densities.

Discussion

The authors acknowledge that this study was limited by the number of sites lacking replication and the possibility that individuals were missed during the field surveys, however the length of the study warrants exploration of the data set.

The most outstanding feature of this long-term data set is the significant decrease in density of *V. erioloba* (>0.2m) individuals at two sites (WP, NoWP) (Figure 1). The most prominent decline was for *V. erioloba* at WP from the early 1980s until the mid-1990s, a period when the mean annual rainfall was below average for most years (Figure S2). This dry period followed on a wet cycle in the late 1970s that preceded the surveys. The large numbers of seedlings could have been the aftermath of the wet cycle and their demise as a result of the following dry cycle in the 1980s. Numerous authors have reported large numbers of *V. erioloba* seedlings following above average rainfall periods (Barnes 2001a, Moustakas et al. 2008, Seymour 2008), however, survival of *V. erioloba* seedlings is very low (Barnes 2001b, Seymour & Milton 2003, Steenkamp et al. 2008, Van der Merwe et al. 2019) due to either drought, frost, herbivory or fire. The low survival of seedlings was supported by the results of this study.

When monitoring commenced, the density of the *V. erioloba* >0.2 m individuals was approximately five-fold higher at WP than to the north thereof and 36-fold higher than at EoWP. Such high densities of saplings are quite uncommon in the interior duneveld (*pers. obs.* N.v.R) and this raises the question as to whether the high densities are in some way associated with the watering point opened in 1959, 21 years prior to the commencement of vegetation monitoring. *Vachellia erioloba*

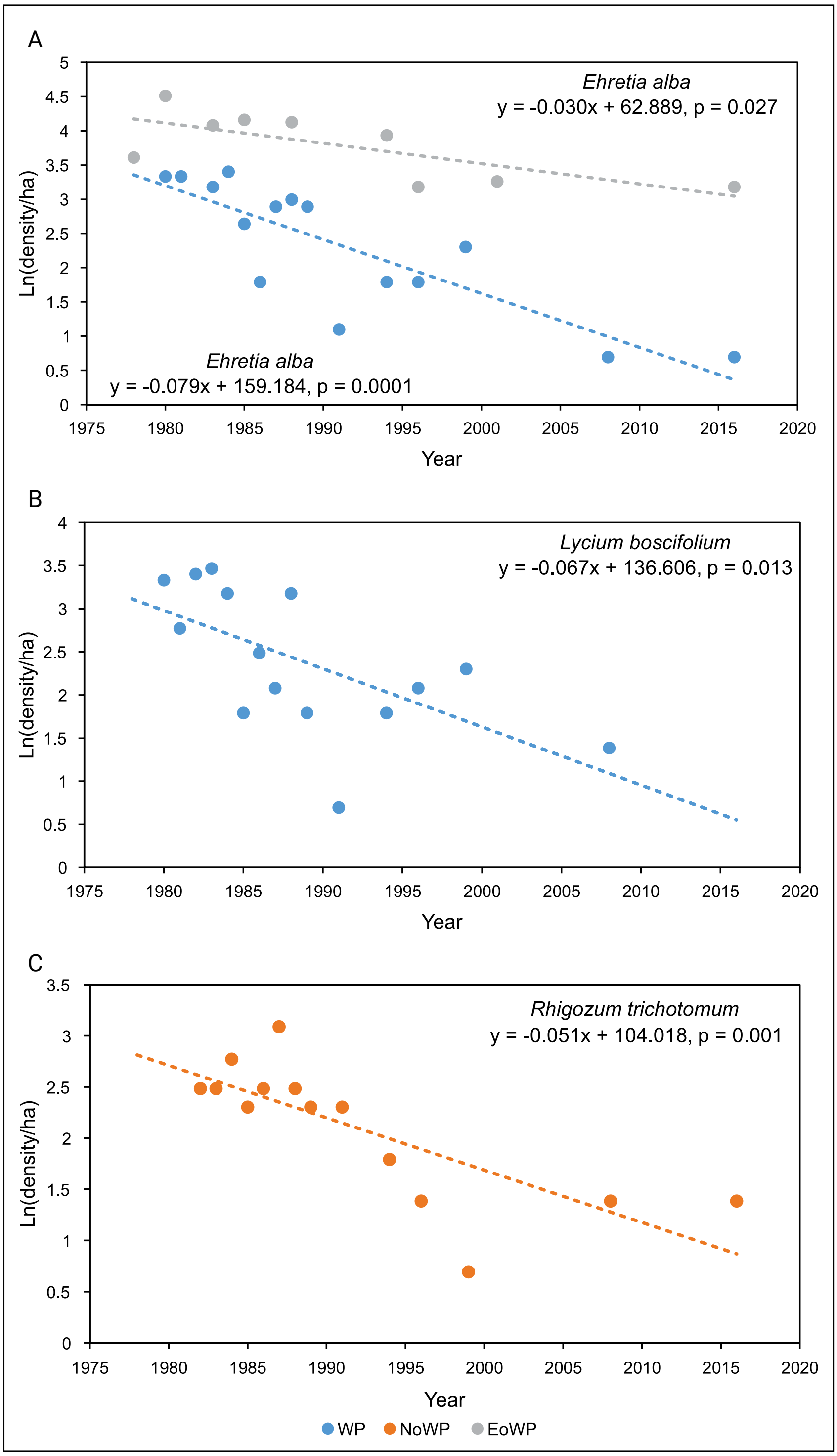

Figure 2. Linear regressions of the natural logarithm of the number of individuals per hectare indicating significant trends in density of shrub species over time. (a) *Ehretia alba*; (b) *Lycium bosciifolium*; and (c) *Rhigozum trichotomum*. WP = Watering point, NoWP = North of watering point, EoWP = East of watering point.

is often perceived by landowners as an encroaching species in the Kalahari (Seymour & Milton 2003) and it could be speculated that this species encroached at the watering point after it was opened and before monitoring started. However, the speculated encroachment did not continue during the monitoring period.

In 2016, the density of *V. erioloba* at WP was 29% and NoWP 19% of the initial density. It is therefore unlikely that borehole drawdown (Shadwell & February 2017) led to the dieback of trees at WP, since a similar decrease also occurred away from the watering point. The large decrease in density in young individuals at WP and NoWP could largely be ascribed to density-dependent self-thinning, whereby density decreases with a concomitant increase in biomass of the remaining individuals (Silvertown & Charlesworth 2001).

At the three sites shrub densities generally decreased significantly or remained relatively constant. Three of these tall shrubby species are often associated with bush encroachment on heavily utilised farmland in the

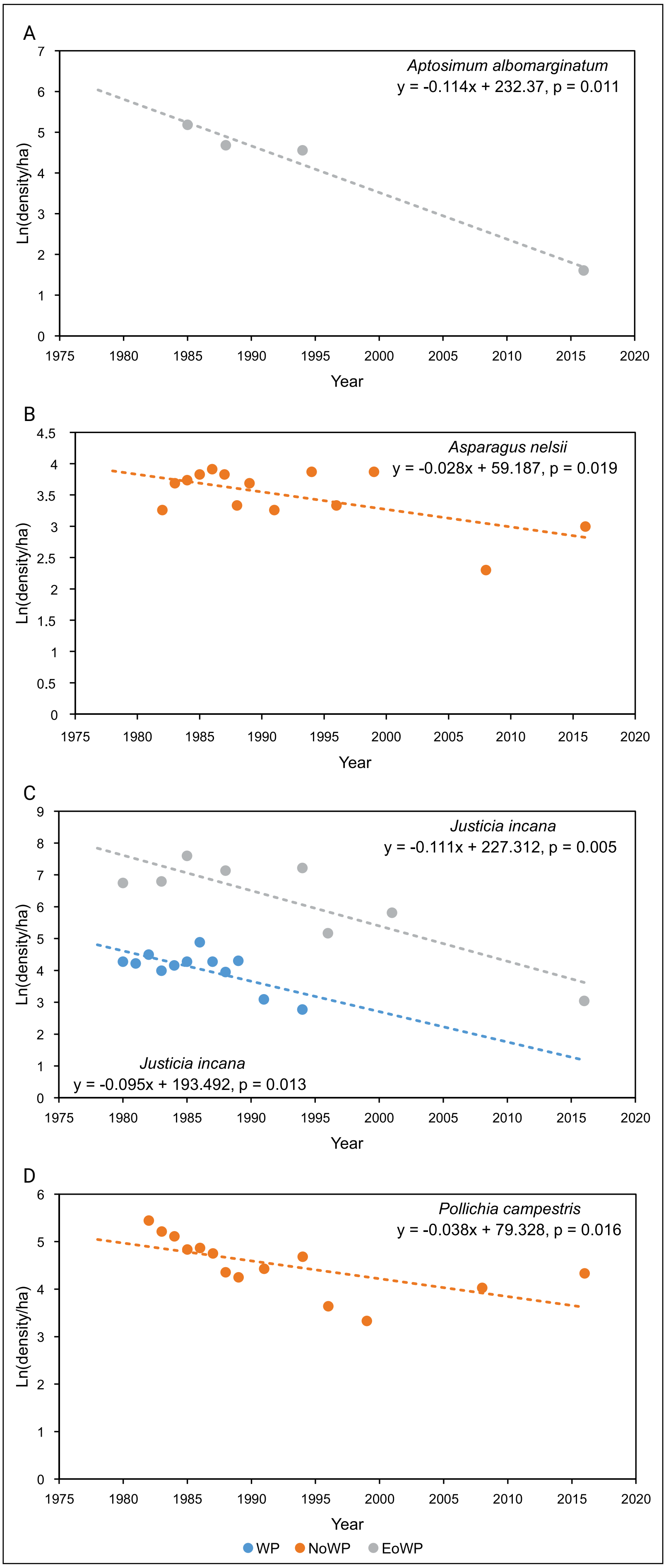

Figure 3. Linear regressions of the natural logarithm of the number of individuals per hectare indicating significant trends in density of dwarf shrub species over time. WP = Watering point, NoWP = North of watering point, EoWP = East of watering point. (a) *Aptosimum albomarginatum;* (b) *Asparagus nelsii*; (c) *Justicia incana*; and (d) *Pollichia campestris*.

Kalahari i.e. *Grewia flava*, *Rhigozum trichotomum* and *Senegalia mellifera* (Joubert et al. 2013, Moleele et al. 2002, Moore et al. 1988, Tews et al. 2004, Van Rooyen et al. 1994). However, densities of these known encroachers remained relatively constant (*G. flava* at WP and EoWP, *S. mellifera* at EoWP) or decreased significantly for *R. trichotomum* (NoWP) over the monitoring period at all sites.

The dwarf shrub densities showed large variability, as large as ten-fold, across the survey period. These fluctuations between high and low densities occurred at shorter time intervals than for the tree species.

Overall, the changes in density of the woody species seem to point to the importance of particular rainfall patterns or sequences of events over different years that are responsible for these changes in the southern Kalahari (Van Rooyen et al. 1990, 1994). Furthermore, the lack of evidence of bush encroachment in this conservation area at the three sites, one of which is situated at a watering point, supports the notion that bush encroachment in arid savannas is driven primarily by land-use practices and not by elevated carbon dioxide levels that are sometimes provided as cause for encroachment (Nackley et al. 2018).

Conclusions

Monitoring was initiated based on a simple passive monitoring question of 'How does vegetation change over time?' The authors acknowledge that such research may be limited in usefulness as cautioned by Lindenmayer and Likens (2010), however, due to the length of the data set, investigation was justified. A similar decline in density of *V. erioloba* tree seedlings and >0.2 m individuals was found at and away from the watering point. Furthermore, the density of known bush encroaching species at the watering point did not increase over the monitored period.

References

Barnes, M.E., 2001a, 'Seed predation, germination and seedling establishment of *Acacia erioloba* in Northern Botswana', *Journal of Arid Environments* 49, 541–554, DOI: 10.1006/jare.2001.0805.

Barnes, M.E., 2001b, 'Effects of large herbivores and fire on the regeneration of *Acacia erioloba* in Chobe National Park, Botswana', *African Journal of Ecology* 39, 340–350, DOI: 10.1046/j.1365-2028.2001.00325.x.

Chambers, L.E., Barnard, P., Poloczanska, E.S., Hobday, A.J., Keatley, M.R., Allsopp, N. & Underhill, L.G., 2016, 'Southern hemisphere biodiversity and global change: data gaps and strategies', *Austral Ecology* 421, 20–30, http://dx.doi.org/10.1111/aec.12391.

Haase, P., Tonkin, J.D., Stoll, S., Burkharde, B., Frenzel, M., Geijzendorffer, I.R., Häuser, C., Klotz, S., Kühn, I., McDowell, W.H., Mirtl, M., Müller, F., Musche, M., Penner, J., Zacharias, S. & Schmeller, D.S., 2018, 'The next generation of site-based long-term ecological monitoring: Linking essential biodiversity variables and ecosystem integrity', *Science of the Total Environment* 613–614, 1376–1384, https://doi.org/10.1016/j.scitotenv.2017.08.111.

Joubert, D.F., Smit, G.N. & Hoffman, M.T., 2013, 'The influence of rainfall, competition and predation on seed production, germination and establishment of an encroaching *Acacia* in an arid Namibian savanna', *Journal of Arid Environments* 91, 7–13, DOI: 10.1016/j.jaridenv.2012.11.001.

Lindenmayer, D.B. & Likens, G.E., 2009, 'Adaptive monitoring – a new paradigm for long-term studies and monitoring', *Trends in Ecology and Evolution* 24, 482–486, DOI: 10.1016/j.tree.2009.03.005.

Lindenmayer, D.B. & Likens, G.E., 2010, 'The science and application of ecological monitoring', *Biological Conservation* 143, 1317–1328, DOI: 10.1016/j.biocon.2010.02.013

Magurran, A.E., Baillie, S.R., Buckland, S.T., Dick, J.M., Elston, D.A., Scott, E.M., Smith, R.I., Somerfield, P.J. & Watt, A.D., 2010, 'Long-term datasets in biodiversity research and monitoring: assessing change in ecological communities through time', *Trends in Ecology and Evolution* 25, 574–582, DOI: 10.1016/j.tree.2010.06.016.

Moleele, N.M., Ringrose, S., Matheson, W. & Vanderpost, C., 2002, 'More woody plants? the status of bush encroachment in Botswana's grazing areas', *Journal of Environmental Management* 64, 3–11, DOI: 10.1006/jema.2001.0486.

Moore, A., Van Eck, J.A.J., Van Niekerk, J.P. & Robertson, B.L., 1988, 'Evapotranspirasie in drie plantgemeenskappe van 'n *Rhigozum trichotomum* habitat te Upington', *Journal of the Grassland Society of southern Africa* 5, 80–84, https://doi.org/10.1080/02566702.1988.9648115.

Moustakas, A., Wiegand, K., Getzin, S., Ward, D., Meyer, K.M., Guenther, M. & Mueller, K.-H., 2008, 'Spacing patterns of an *Acacia* tree in the Kalahari over a 61-year period: How clumped becomes regular and *vice versa*', *Acta Oecologica* 33, 355–364, DOI: 10.1016/j.actao.2008.01.008.

Nackley, L.L., Betzelberger, A., Skowno, A., West, A.G., Riley, B.S., Bond, W.J. & Midgley, G.F., 2018. 'CO_2 enrichment does not entirely ameliorate *Vachellia karroo* drought inhibition: A missing mechanism explaining savanna bush encroachment', *Environmental and Experimental Botany* 155, 98–106, DOI: 10.1016/j.envexpbot.2018.06.018.

Parr, T.W., Ferretti, M., Simpson, I.C., Forsius, M. & Kovács-Láng, E., 2002, 'Towards a long-term integrated monitoring programme in Europe: network design in theory and practice', *Environmental Monitoring and Assessment* 78, 253–290, DOI: 10.1023/a:1019934919140.

Peters, D.P.C., Loescher, H.W., SanClements, M.D. & Havstad, K.M., 2014, 'Taking the pulse of a continent: expanding site-based research infrastructure for regional- to continental scale ecology', *Ecosphere* 5, 1–23, http://dx.doi.org/10.1890/ES13-00295.1.

Seymour, C., 2008, 'Grass, rainfall and herbivores as determinants of *Acacia erioloba* (Meyer) recruitment in an African Savanna', *Plant Ecology* 197, 131–138, DOI: 10.1007/s11258-007-9366-x.

Seymour, C. & Milton, S., 2003. '*A collation and overview of research information on* Acacia erioloba *(camelthorn) and identification of relevant research gaps to inform protection of the species*', Department of Water Affairs and Forestry, Pretoria.

Shadwell, E. & February, E., 2017, 'Effects of groundwater abstraction on two keystone tree species in an arid savanna national park', *Peer J* 5, e2923, DOI 10.7717/peerj.2923.

Silvertown, J. & Charlesworth, D., 2001, '*Introduction to plant population biology*', 4th edn., Blackwell Science.

Steenkamp, C.J., Vogel, J.C., Fuls, A., Van Rooyen, N. & Van Rooyen, M.W., 2008, 'Age determination of *Acacia erioloba* trees in the Kalahari', *Journal of Arid Environments* 72, 302–313, DOI: 10.1016/j.jaridenv.2007.07.015.

Tews, J., Schurr, F., Jeltsch, F. & Skarpe, C., 2004, 'Seed dispersal by cattle may cause shrub encroachment of *Grewia flava* on southern Kalahari rangelands', *Applied Vegetation Science* 7, 89–102, DOI: 10.1111/j.1654-109X.2004.tb00599.x.

Van der Merwe, H., Van Rooyen, N., Bezuidenhout, H., Bothma, J. du P. & Van Rooyen, M.W., 2019, '*Vachellia erioloba* dynamics over 38 years in the Kalahari Gemsbok National Park, South Africa', *Koedoe* 61(1), a1534, DOI: 10.4102/koedoe.v61i1.1534.

Van Rooyen, N. & Van Rooyen, M.W., 1998, 'Vegetation of the South-western arid Kalahari: an overview', *Transactions of the Royal Society of South Africa* 53, 113–140, https://doi.org/10.1080/00359199809520381.

Van Rooyen, N., Bredenkamp, G.J., Theron, G.K., Bothma, J du P. & Le Riche, E.A.N., 1994, 'Vegetational gradients around artificial watering points in the Kalahari Gemsbok National Park', *Journal of Arid Environments* 26, 349–361, https://doi.org/10.1006/jare.1994.1037.

Van Rooyen, N., Bezuidenhout, H., Theron, G.K. & Bothma, J du P., 1990. 'Monitoring of the vegetation around artificial watering points (windmills) in the Kalahari Gemsbok National Park, *Koedoe* 33, 63–88, https://doi.org/10.4102/koedoe.v33i1.453.

Van Rooyen, M.W., Van Rooyen, N., Bothma, J. du P. & Van den Berg, H., 2008, 'Landscapes in the Kalahari Gemsbok National Park, South Africa', *Koedoe* 50, 99–112, DOI: 10.4102/koedoe.v50i1.154.

Supplementary Material

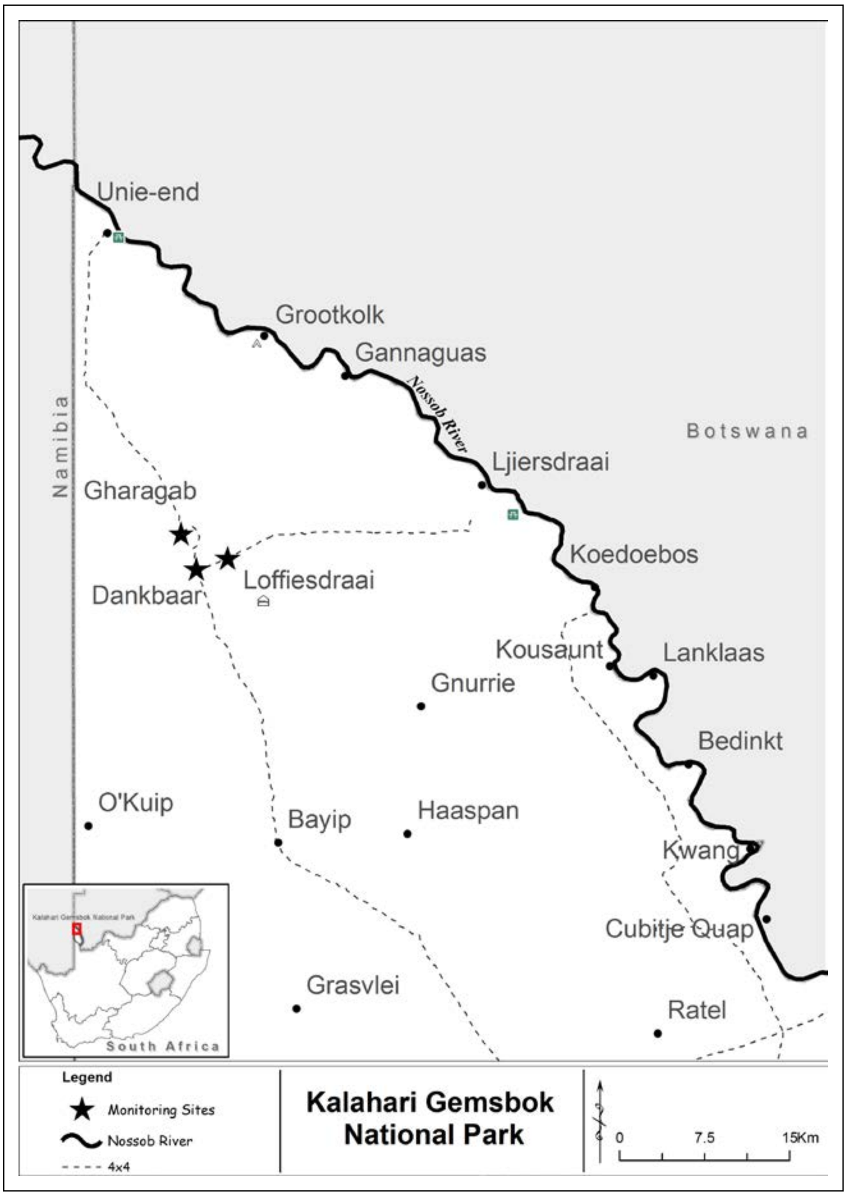

FIGURE S1: Location of the Dankbaar artificial watering point and two sites situated 5 km to the north and east of the watering point in the Kalahari Gemsbok National Park.

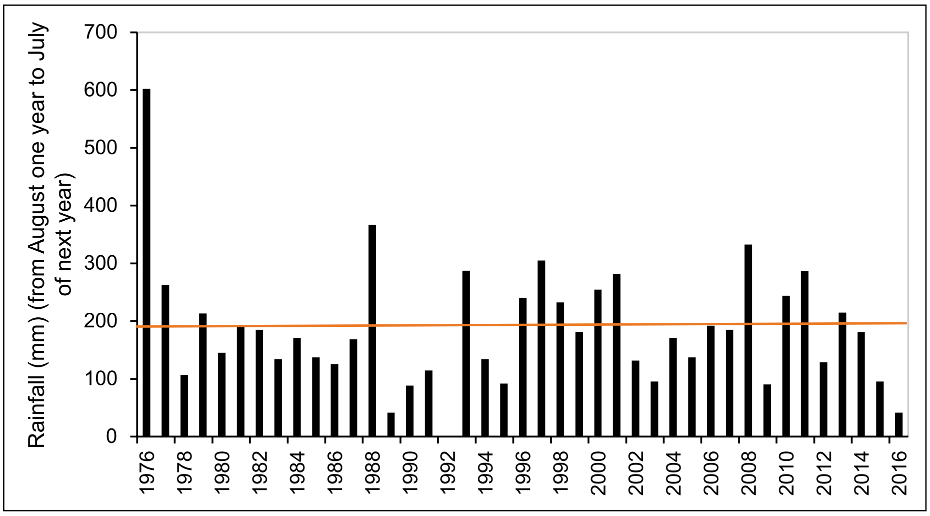

FIGURE S2: Seasonal rainfall (August of one year to July of the next year) at Nossob Rest Camp from 1976 until 2016. Orange line represents the mean annual rainfall of 194 mm (standard deviation ±88.8 mm). Data provided by the South African National Parks.

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Long-term changes in forest cover in a global biodiversity hotspot in southern Mozambique

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Background: Deforestation is a complex and dynamic process of widespread concern in sub-Saharan Africa that is influenced by a range of social, economic and biophysical factors.

Objectives: The aim of this study was to analyse patterns of deforestation and its potential drivers in the Licuáti Forest Reserve, a biodiversity hotspot in southern Mozambique, between 1990 and 2016.

Method: We performed image classification on Landsat imagery at six time steps and interviewed local community members to understand the spatial pattern and rate of forest cover loss over time. We also examined changes in the incidence of fire.

Results: A substantial increase in the rate of deforestation since 1990 was detected in this vulnerable thicket vegetation. The probability of deforestation was significantly higher near the major roads, where houses are located. This suggests that the proximity of human settlements to the forest, and access to charcoal markets in urban areas, influenced the spatial pattern. Two key factors, charcoal production and the establishment of settlements and agricultural lands, were identified as proximate causes of deforestation. In addition, fires associated with these two causes might amplify the loss of forests in the area.

Conclusions: Complex interactions between the drivers of deforestation and socio-economic factors were suggested, as most of the charcoal produced in the region is transported to Maputo. Ongoing road improvements and infrastructural development in the region will likely accelerate the decline in forest cover in the future. This has implications for the biodiversity of the region as well as for the sustainability of local livelihoods, as they often depend on forest products for their daily uses.

Keywords: charcoal production; deforestation; Maputaland; remote sensing; traditional authority

Introduction

Deforestation is a major environmental concern in sub-Saharan Africa. However, it is a complex and dynamic process influenced by many different social, economic and biophysical factors (Geist & Lambin 2002; Kleemann et al. 2017; Woollen et al. 2016). In addition, the sustainability of forest resources is influenced by the type of disturbance, the ability of different species to regrow, and by climatic conditions (Tredennick & Hanan 2015; Wollen et al. 2016). While some of the drivers of deforestation (e.g. population growth and rapid urbanisation) might be common within a region or continent (Geist & Lambin 2002; Hosonuma et al. 2012; Rudel 2013), its impact on local livelihoods is likely to be case specific (Woollen et al. 2016).

Because of the various functions and roles of forests, the effect of deforestation can result in a decline in essential ecosystem services (Ryan et al. 2016). These include the provision of timber and water, climate regulation, carbon sequestration, and the safeguarding of biodiversity (Hansen et al. 2013; Millennium Ecosystem Assessment 2005; Turner, Lambin & Reenberg 2007). In sub-Saharan Africa, a reduction in forest cover can also directly affect the livelihoods of millions of people. Rural households often depend on many different goods and services from forests, including fuelwood, food, and medicine for their domestic use or as a source of income (e.g. Bandyopadhyay, Shyamsundar & Baccini 2011; Cavendish 2000). Furthermore, in urban areas, charcoal derived from forest trees is still a major energy source used for cooking (Zulu & Richardson 2013). Past studies have suggested that charcoal production, fuelwood extraction, timber harvesting and the expansion of agricultural fields are key proximate causes of deforestation. These factors, in turn, are influenced by several important socio-economic changes in a country or region, such as population growth, urbanisation and economic growth (Ahrends et al. 2010; Burgess et al. 2017; Hosonuma et al. 2012; Mayaux et al. 2013; Rudel et al. 2009). The effects of these socio-economic changes on deforestation have been investigated mainly at national scale (e.g. DeFries et al. 2010; Rudel 2013), and regional scale studies are still limited in sub-Saharan Africa (Ryan, Berry & Joshi 2014).

This study focused on the Licuáti Forest Reserve in southern Mozambique. We investigated the historical pattern and rate of deforestation and its potential drivers using remote sensing techniques and an interview survey undertaken with local inhabitants. Due to a diverse biota and high endemism of species, the region has been recognised as a global biodiversity hotspot (Siebert et al. 2002; Steenkamp et al. 2004; Van Wyk 1996). At the same time, the prevalence of extreme poverty is an important social issue, with more than 40% of the rural population living below the poverty line (Alfani et al. 2012; Direcção Nacional de Estudos e Análise de Políticas 2010). Many of the rural households in the study area depend on natural resources from the surrounding forests for their livelihoods (Kloppers 2001; Soto, Munthali & Breen 2001). Furthermore, people's livelihoods and forest uses have changed substantially since 1992 when the decades-long civil war ended. The end of conflict triggered rapid economic growth in the country and has led to important changes in land-use practices, such as land and infrastructure development, and increased harvesting of natural resources in the region (Kloppers 2001; McGregor 1998; Siebert et al. 2002). One of the major consequences of the socio-economic and demographic changes in post-civil war Mozambique has been the rapid loss of forest cover, which declined by 0.58% per annum between 1990 and 2002 (Sitoe, Salomão & Wertz-Kanounnikoff 2012). Although information about deforestation is available globally since 2000 (Hansen et al. 2013), little is known about the reasons for forest cover change, especially at local-level. Long-term analyses of forest cover change, therefore, need to be contextualised in terms of how anthropogenic pressures might have influenced such changes.

Our aim in this study was to: 1) map and quantify the historical pattern of deforestation in rural southern Mozambique after the civil war to the present (1990–2016); 2) identify potential drivers of deforestation and discuss their effects in a socio-ecological context; and 3) provide future perspectives on how the use of natural resources impacts further on the environment. The results provide fundamental information to better plan and conserve natural resources and livelihoods in the region, as well as to help anticipate potential future changes.

Method

Study area

The Licuáti Forest Reserve (LFR) is located in Matutuine District in southern Mozambique, approximately 50 km south of Maputo, the capital city of Mozambique (Figure 1A). In southern Mozambique, mean annual rainfall declines from east to west with approximately 1 100 mm falling along the coastline and 600 mm further inland in the LFR (Izidine, Siebert & Van Wyk 2003; Van Wyk 1996). The land is mostly flat and comprises predominantly of aeolian sand. Along the Maputo and Tembe rivers, however, alluvium clayey soils, which are more suitable for farming, are also common (Izidine et al. 2003).

The LFR contains floristically unique Licuáti Thicket (also known as Short Sand Forest) and Licuáti Forest (Tall Sand Forest), and forms the core of the Maputaland Centre of Endemism. This is a region within the Maputaland–Pondoland–Albany biodiversity hotspot where high levels of endemism and biodiversity have been recognised (Izidine et al. 2003; Van Wyk 1996). At least 35 Maputaland endemic species have been recorded in the LFR, and among these, 20 species have restricted distributions in the reserve (Izidine 2003). Licuáti Thicket is a particularly important habitat for many endemic species in the region. It is characterised by dense woody vegetation in the shrub layer, which occurs to a height of 5–6 m (Gaugris & Van Rooyen 2008). Common species in the shrub layer include *Psydrax locuples*, *P. fragrantissima* and *Warneckea parvifolia,* while *Balanites maughamii* and *Afzelia quanzensis* emerge above the canopy. Licuáti Forest has similar species composition but has a taller structure up to 15 m in height. These two vegetation types, Licuáti Thicket and Licuáti Forest, are typically located in a matrix of open woodland dominated by *Terminalia sericea*, *Albizia versicolor, Albizia adianthifolia* var. *adianthifolia* or grassland, which is structurally and floristically different (Izidine 2003; Siebert et al. 2002) and does not form part of this analysis.

Historically, the Licuáti Thicket and Licuáti Forest have been considered sacred with logging controlled by traditional leaders (Izidine 2003; Izidine et al. 2008). In 1943, the colonial government designated the area as a forest reserve to protect the commercially valuable *Afzelia quanzensis*, which was common in the LFR at the time. The boundary of the LFR is not clearly defined, but widely recognised among local people as the area between Tembe and Maputo rivers and the Bela Vista–Boane and Bela Vista–Catuane roads (Izidine et al. 2009).

During the period of Mozambican civil war (1976–1992), rural areas in southern Mozambique were depopulated. Many people evacuated to the neighbouring countries or cities, and 72% of the current population of Matutuine District had lived elsewhere during this period (Kloppers 2001; McGregor 1998). The vegetation appeared to have recovered over this period as a result of the lower population and less intense pressure from human activities (Siebert et al. 2002), although charcoal production, which started as early as 1979, continued throughout the war (McGregor 1998). After the ceasefire in 1992, people returned from refugee camps and neighbouring countries and agricultural lands were quickly reopened (Sitoe et al. 2012; Smith et al. 2008).

It has been a concern in recent years that intensified human pressure has caused degradation and deforestation in the LFR. It was reported that the LFR has not been functioning as a reserve due to the lack of effective management and monitoring in recent years (Izidine et al. 2009). The potential direct threats noted were the selective logging of commercially valuable timber species, charcoal production, and land development (Izidine et al. 2003; Siebert et al. 2002). Fires also pose a direct threat to the vegetation of the LFR (Izidine 2003), particularly if they increase in frequency.

Deforestation mapping

Data and pre-processing

A total of six cloud-free and terrain-corrected (L1T) Landsat TM, ETM+ and OLI images were downloaded from USGS Earth Resources Observation and Science (EROS) Center Science Processing Architecture (ESPA) system (https://espa.cr.usgs.gov/) (Supplementary Information, Table 1). Top of atmosphere radiance imagery was used. To reduce error caused by phenological variation, all the images selected were from the late growing season (April to June), when cloud cover was also relatively low. The floodplain along the Maputo River (approximately 15 m in elevation) was excluded from the analysis, because discussions with members of the surrounding communities indicated that most of the land had been used for the cultivation of rice prior to 1990. The images were clipped to encompass the study area, and then six bands were used for the following analysis: RGB, NIR, SWIR1 and SWIR2.

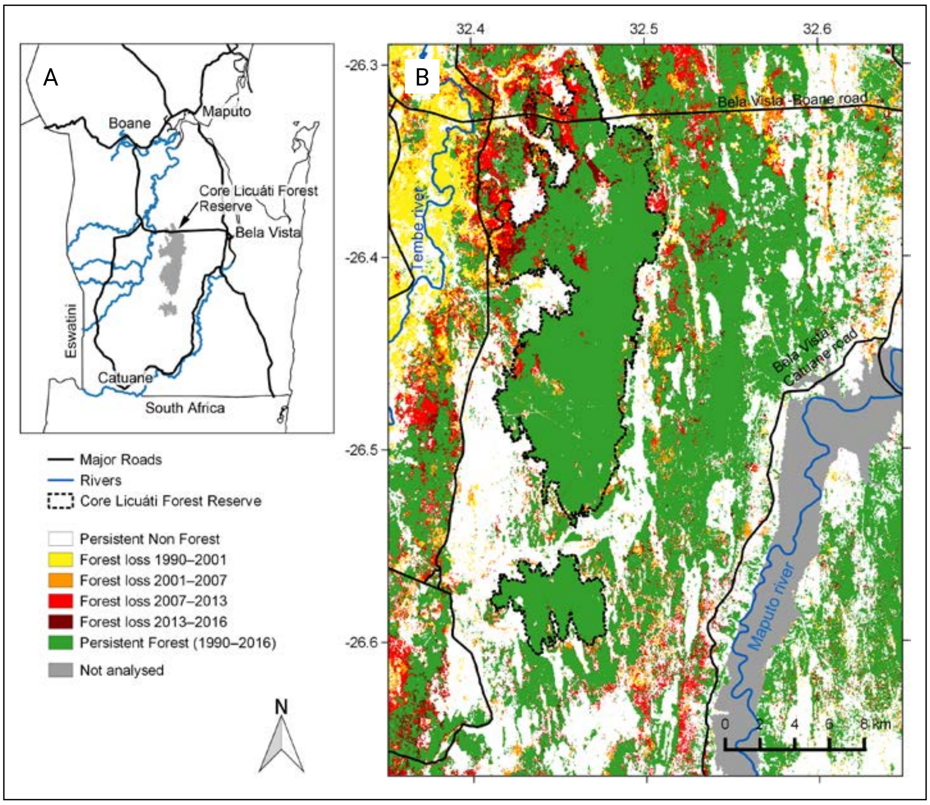

Figure 1. (A) Location of the Licuáti Forest Reserve in southern Mozambique, and (B) deforestation map for the study area between 1990 and 2016. The Core Licuáti Forest Reserve is shown as the two patches of almost contiguous green vegetation outlined in black, running from north to south and slightly left of centre in the image. Green colour indicates the extent of forest cover in 2016.

Analysis

A map of deforestation over the period 1990 to 2016 was produced using a combination of unsupervised and supervised image classification techniques. A flowchart of the procedure followed in this analysis is provided in Supplementary Information, Figure 1. Firstly, six bands of each time step of the Landsat image were classified into 30 spectral classes, which could adequately differentiate forest cover across the study site, applying the k-means algorithm of unsupervised classification. Next, the 30 spectral classes were merged into three information classes: forest, not forest, and unknown, based on user knowledge of the area and image interpretation to true-colour composited from the same set of the Landsat images. In this study, we defined forest as the areas covered by more than 70% by woody plants, and treated Licuáti Thicket and Licuáti Forest as one class (forest). This differentiated the structure of Licuáti Thicket and Licuáti Forest from the other vegetation types (e.g. open woodland). Secondly, a training dataset was generated from the images produced by the previous step. The pixels labelled as 'unknown' at the previous step were excluded from the training dataset. The rest of the pixels were assigned to one of six classes; persistent not forest, deforestation between 1990 and 2001, deforestation between 2001 and 2007, deforestation between 2007 and 2013, deforestation between 2013 and 2016, or persistent forest. For example, a pixel identified as 'forest' in 1990 and then 'not forest' over the period 2001 to 2016 was classed as 'deforestation between 1991 and 2001', and a pixel classified as 'forest' for all five time steps was categorised as 'persistent forest'. This study assumed that after deforestation, the transition from 'not forest' to 'forest' did not occur during the period over which our study took place and pixels indicating regrowth (transition from 'not forest' to 'forest') were excluded from the training data set. This assumption was based on the understanding that Licuáti Thicket and Licuáti Forest are very stable over time (Izidine 2003; Matthews et al. 2001) and has not expanded during the period of analysis. It is also based on our observations in the field of the irreversibility of deforestation and the unidirectional nature of land use change. After this, 300 pixels were randomly selected for each class, and then split into 200 training pixels and 100 validation pixels. Finally, all the Landsat images (six bands, five time steps) were stacked together and a direct supervised classification was performed with a support vector machine (SVM) using 'rasclass' package (Wiesmann & Quinn 2016) in R (ver 3.1.0, R Core Team 2014).

The forest extent and deforested area were estimated from the deforestation map produced following the approach outlined above. The mean annual deforestation rate was calculated using the compound interest formula (Puyravaud 2003, Supplementary Information). The pattern of deforestation was analysed for the entire study area and the floristically important Core Licuáti Forest Reserve (CLFR) separately. The CLFR was defined as comprising the two biggest patches of the mosaic of Licuáti Thicket and Licuáti Forest, and followed the approach of Izidine (2003) who identified these patches by visual interpretation of aerial photos (Figure 1B). To understand the influence of the roads, the distance from the major roads to each pixel was measured in QGIS (ver 2.10.1 Pisa). From this, the probability of forest loss (response variable) was tested against the distance from the major roads (explanatory variable) using the logistic regression model for each time step. Statistical analysis was implemented in R (R Core Team 2014).

An assessment of accuracy was performed comparing the classified deforestation map and validation dataset. In addition, forest cover in 2013 and 2016 was validated independently using very high resolution imagery from Google Earth (ver 7.1.7.2606, Google Inc) and a true colour composite Sentinel-2 image from the Sentinel Scientific Data Hub (https://scihub.copernicus.eu) captured within four months from the date of the Landsat imagery.

Visual interpretation of very high resolution images

To understand the causes of deforestation in the LFR, visible disturbances, including fire, charcoal kilns, roads and tracks, were interpreted from very high resolution images from Google Earth and then marked on the map in selected locations. The imagery used for this analysis was taken in early 2000s and September 2015. In addition, the locations of all houses in the study area were recorded from Google Earth images obtained from August to September 2015. In this study a house was defined as an artificial roofed structure larger than 3 m × 3 m. No distinction was made between schools, hospitals, and other public buildings because those were indistinguishable from other dwellings in the satellite images. Then, the point data indicating the locations of houses was rasterised at 30 m spatial resolution, and the distance from the major roads to each pixel in which a house or group of houses was located, was measured in QGIS (ver 2.10.1 Pisa). To test if the proximity of roads influenced the spatial distribution of houses, the presence or absence of houses in each pixel was regressed against the distance from the major roads using a logistic regression model.

Fire history

A fire history map was produced using MODIS burned area monthly product (MCD45A1). The data for the period January 2001 to December 2015 were downloaded from Earth Explorer (http://earthexplorer.usgs.gov/), following which burned areas were mapped across the study area. The number of fire occurrences and the size of the burned area were estimated at five year intervals for the study area, for a 1 km buffer area around the CLFR, as well as for the CLFR separately.

Interviews with leaders, government representatives and resource users

Semi-structured interviews were conducted in March 2016 with 30 members of the local community to understand the uses, current regulation, and enforcement of resource use protocols within the LFR. Interviewees included three traditional leaders, one government representative, seven community officials, eight charcoal producers, and 11 other members of the local community. The traditional leaders were selected from Pochane, Jabula and Tinonganine, which are all localities within the LFR. The interviews were undertaken with each community member separately or in small groups of two to five people, depending on the attendance of the interviewees.

Field observations

Fallen trees, charcoal kilns and other processes related to charcoal production were recorded in the field. The location and the number of charcoal bags were also counted along the major roads during the course of traversing the region. Field surveys were undertaken on two separate occasions; in October 2015 and March 2016.

Results

Pattern of deforestation

The extent of forest cover in the study area has decreased from 772.7 km^2 in 1990 to 549.1 km^2 in 2016. The annual rate of deforestation has increased from 0.8% in 1990–2001 to 2.3% in 2013–2016, suggesting intensified deforestation in recent years (Table 1). In the Core Licuáti Forest Reserve (CLFR), the annual rate of deforestation was relatively low and stable before 2007, but has increased since this date to match that of the wider study area. The CLFR has lost 13% of its extent over the past 25 years.

The pattern of deforestation illustrated in Figure 1B shows that more severe deforestation has occurred in the western and northern part of the study area, especially within the area along the Tembe River and the Bela Vista–Boane Road. There was a significant effect of the distance from the major roads on the probability of deforestation for all the periods ($p < 0.001$, see Table 2 for the details). The deforestation hotspots (i.e. areas of greatest loss in forest cover) have also shifted over the past 25 years. Between 1991 and 2001, forest loss occurred mostly in the area near the Tembe River. However, since 2001, forest loss has taken place at multiple locations near the major roads and has been advancing further from the roads over time (Figure 2).

The overall accuracy of the classification approach used was estimated at 98% while the kappa coefficient was 0.98. An independent accuracy assessment for forest cover based on Google Earth high resolution imagery and Sentinel-2 imagery resulted in an overall accuracy of 86% in 2013 and 91% in 2016 (see Supplementary Information, Tables 2–4 for the details).

Table 1. Changes in the extent of forest (km^2) and in the annual rate of deforestation (%) in the wider study area as well as the Core Licuáti Forest Reserve (CLFR) in southern Mozambique estimated by an analysis of Landsat imagery between 1991 and 2016

	Period	Area	
		Study area	**Core Licuáti Forest Reserve**
Forest extent (km^2)	1990	772.7	159.0
	2001	706.4	156.9
	2007	663.0	154.5
	2013	588.6	145.8
	2016	549.1	137.7
Annual deforestation (%)	1990–2001	0.8	0.1
	2001–2007	1.1	0.3
	2007–2013	2.0	1.0
	2013–2016	2.3	1.9

Table 2. Statistical summary of logistic regression models testing the effect of distance from the major roads (explanatory variable) on the probability of forest loss in four time steps and distribution of houses (response variables)

Response variables	**Period**	**$\chi2$**	**df**	***p* value**
Forest loss	1990–2001	50323	858550	< 0.001
	2001–2007	9291	784867	< 0.001
	2007–2013	35672	736702	< 0.001
	2013–2016	12594	653972	< 0.001
Houses	-	3529	1445474	< 0.001

df: degrees of freedom

Visual interpretation of the disturbances

Multiple human disturbances, including charcoal production, fire, establishment of new settlements and small scale agriculture, were observed in the satellite

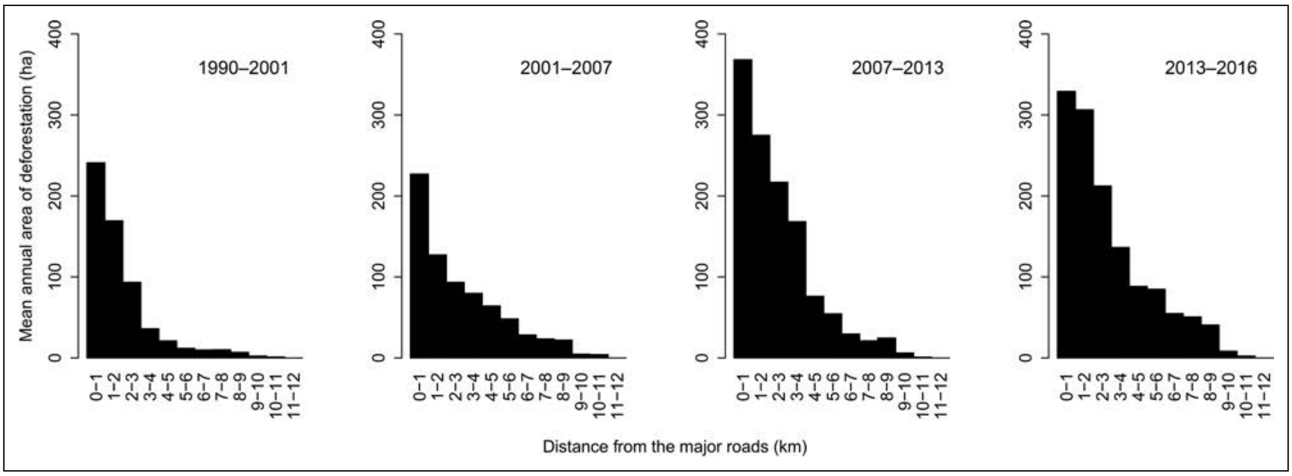

Figure 2. Changes in the mean annual area (ha) of deforestation in the wider study area around the Licuáti Forest Reserve in southern Mozambique in different distance classes from the major roads between 1990 and 2016. Distance classes were segmented in 1 km intervals.

images (Figure 3). Small scale agriculture and houses were normally found within a short distance from the major roads (Figure 3A, B). Charcoal kilns were mostly located in the CLFR, notably around former emerging trees (Figure 3C). Commonly, charcoal kilns were found prior to the occurrence of larger scale forest clearing (Figure 3A, B). Fires of various sizes were observed from the edge of the forest and thicket as well as near the deforested area.

The causes of the fire were not visible from the images, but the location of the burned area implied that charcoal production and land clearing to create open space for agriculture were the major causes of the fires. Typically, the network of roads and tracks penetrated into the CLFR to connect the charcoal kilns, agricultural fields, houses and major roads.

Houses were distributed throughout the study area but were significantly confined to locations near the major roads ($p < 0.001$, Table 2) (see Supplementary Information, Figure 2). Of the 6,008 houses counted, 51.3% were located within 500 m of a major road. The location of villages and larger settlements overlapped with deforestation hotspots.

Fire history

Frequent fires were observed near the Maputo and Tembe rivers where lands are used predominantly for agricultural production (see Supplementary Information, Figure 3). Fire was recorded only occasionally in the CLFR between 2001 and 2005, and relatively infrequently in the surrounding 1 km buffer during this time step. Over time, however, the trend has been for an increase in fire frequency, especially in the northeastern part of the study area (Table 3). However, many of the relatively small scale fires were not detected in this product, as burned areas observed by the visual interpretation of high resolution images (Figure 3) were not recorded by the MODIS burned area product.

Table 3. Size of burned area and the number of fires within a 1 km buffer area around the Core Licuáti Forest Reserve (CLFR) as well as in the CLFR itself in southern Mozambique estimated by MODIS burned area product (MCD45A1) in three time steps between 2001 and 2015

	Period		
	2001–2005	**2006–2010**	**2011–2015**
Area burned (km^2)			
Study area	131.6	133.7	194.1
Buffer (1 km from CLFR)	0.7	13.9	25.0
Core Licuáti Forest Reserve (CLFR)	0.0	2.1	11.7
Number of fires			
Study area	133	130	166
Buffer (1 km from CLFR)	2	15	26
Core Licuáti Forest Reserve (CLFR)	0	7	17

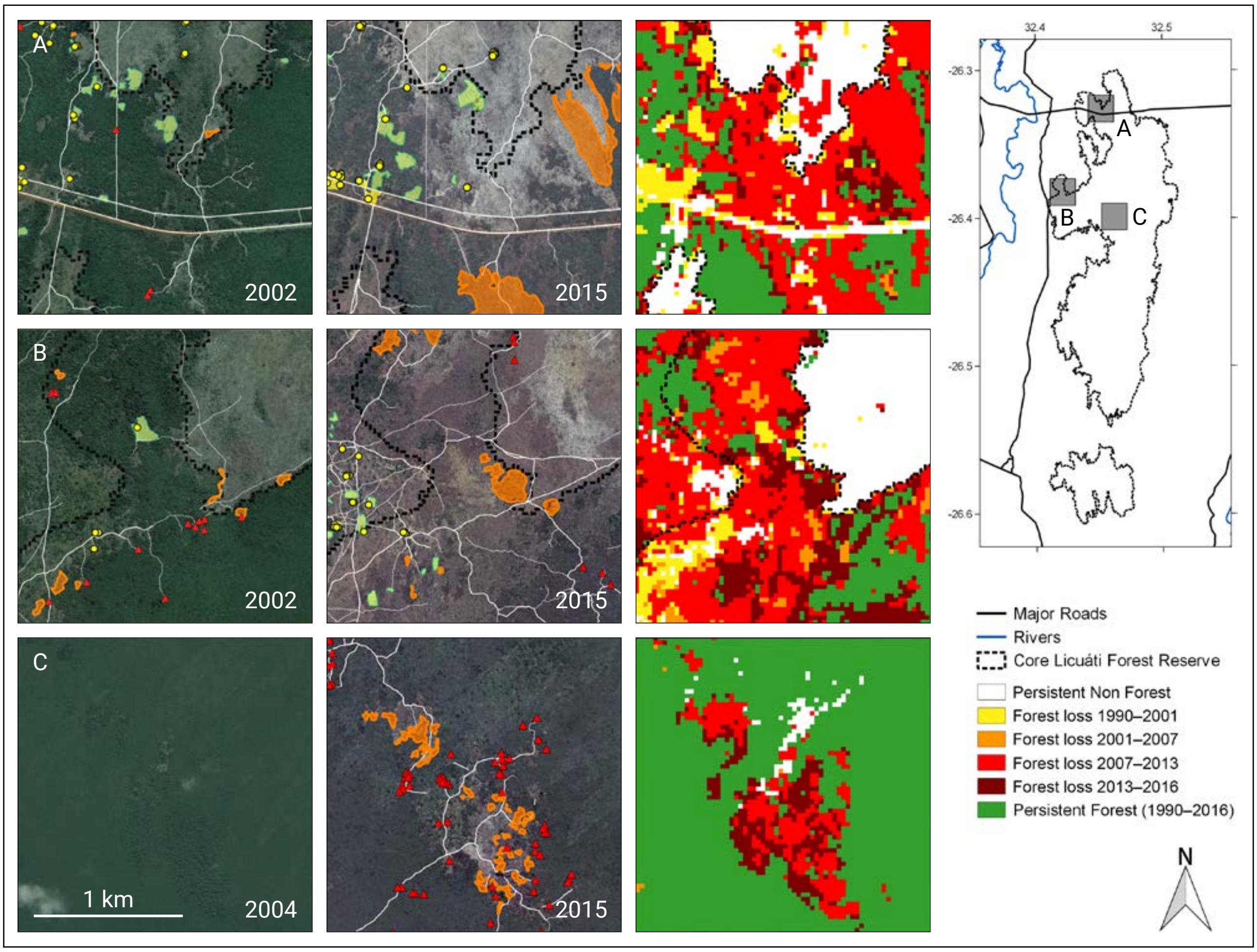

Figure 3. Examples of high resolution Google Earth images of selected areas located primarily within the Core Licuáti Forest Reserve and where forest loss has been prominent since 1991. Images in the left columns were obtained in 2002 and 2004, and the middle column in 2015, while images in the right column show a deforestation map produced from Landsat images. For each of the historical images, the disturbances were visually interpreted and outlined as reflecting a road or path (white line, with dotted line for the narrower paths), fire (orange polygon), charcoal kiln (red triangle), houses (yellow circle and area) and agriculture land (green area). Note that colour and contrast of the historical images were enhanced to improve visibility.

Interviews with leaders, government representatives and resource users

Local inhabitants of the study area indicated that they are allowed to extract resources from the forest including medicinal plants, building material, firewood and charcoal. Many of the respondents suggested that exploitation of forest resources in the study area started before independence in 1975. Resources were mainly exploited to fulfil the basic needs at local level and, because of this, the impacts had been relatively low. However, the rapid increase in human population in both rural and nearby urban areas, together with shortages of food resulting from long periods of drought, has led to the overexploitation of natural resources, particularly wood for charcoal production. Respondents indicated that charcoal produced in the study area is often sold to dealers and transporters from the nearby cities of Matola and Maputo. Currently, the extraction of wood for charcoal production is turning into a small industry. Local inhabitants also suggested that many people who do not reside in the area have invaded the LFR with more sophisticated equipment, including vehicles and chainsaws, to produce charcoal from the woody plants in the study area.

The Mozambican government has worked closely with local communities within the LFR area in the past to ensure the sustainable exploitation of natural resources. Certain members of the communities were appointed as 'community rangers' and were tasked with patrolling the forest to control fire and illegal timber exploitation, and to avoid the cutting of non-authorised tree species. Trees with edible fruits such as *Dialium schlechteri* as well as timber species such as *Afzelia quanzensis* were not allowed to be harvested for the production of charcoal. This regulation is widely recognised among the surrounding communities. For more than 10 years, 12 members of the community from the Pochane area, for example, worked to patrol the forest. However, at present none of them is still active primarily because of a lack of incentives. The absence of community rangers has enabled outsiders to access the CLFR to exploit trees for the production of charcoal regardless of whether they are edible or timber species.

The three traditional leaders interviewed suggested that the sacred sites within the LFR had historically always been respected by local communities. However, the presence of outsiders has meant that the beliefs and practices that preserved some of the forest patches within the CLFR are becoming less effective.

Field observations

Charcoal kilns were frequently observed in the LFR. Typically, tall trees such as *Afzelia quanzensis*, *Balanites maughamii*, *Dialium schlechteri* and *Newtonia hildebrandtii*, with stems larger than 50 cm in diameter were the prime target for the production of charcoal. Usually, all vegetation growing within 10–15 m radius from the target tree was cleared, and all trees with stem diameters larger than 15 cm were cut to produce charcoal (Figure 4A). Cut trees were stacked in mounds 5 to 10 m in diameter and then covered with soil and set alight to create a kiln, which burned for several days (Figure 4B, C). Little recruitment of vegetation was found around the kilns even after several years.

The bags of charcoal collected from the kilns were sold along the main roads, which extend from the large cities (Maputo and Matola) to LFR (Figure 4D; Supplementary Information, Figure 4). A total of 937 and 1 074 bags of charcoal were counted along the major roads around LFR in October 2015 and March 2016 respectively. One bag of charcoal was usually made up of two polypropylene woven bags (each of which is 50 × 120 cm and commonly used for the containment of 30 kg of grain) stitched together to pack charcoal (Figure 4D). The price of charcoal in March 2016 was 250 MT (approximately USD 5) per bag near the LFR and 600 MT per bag in the urban markets.

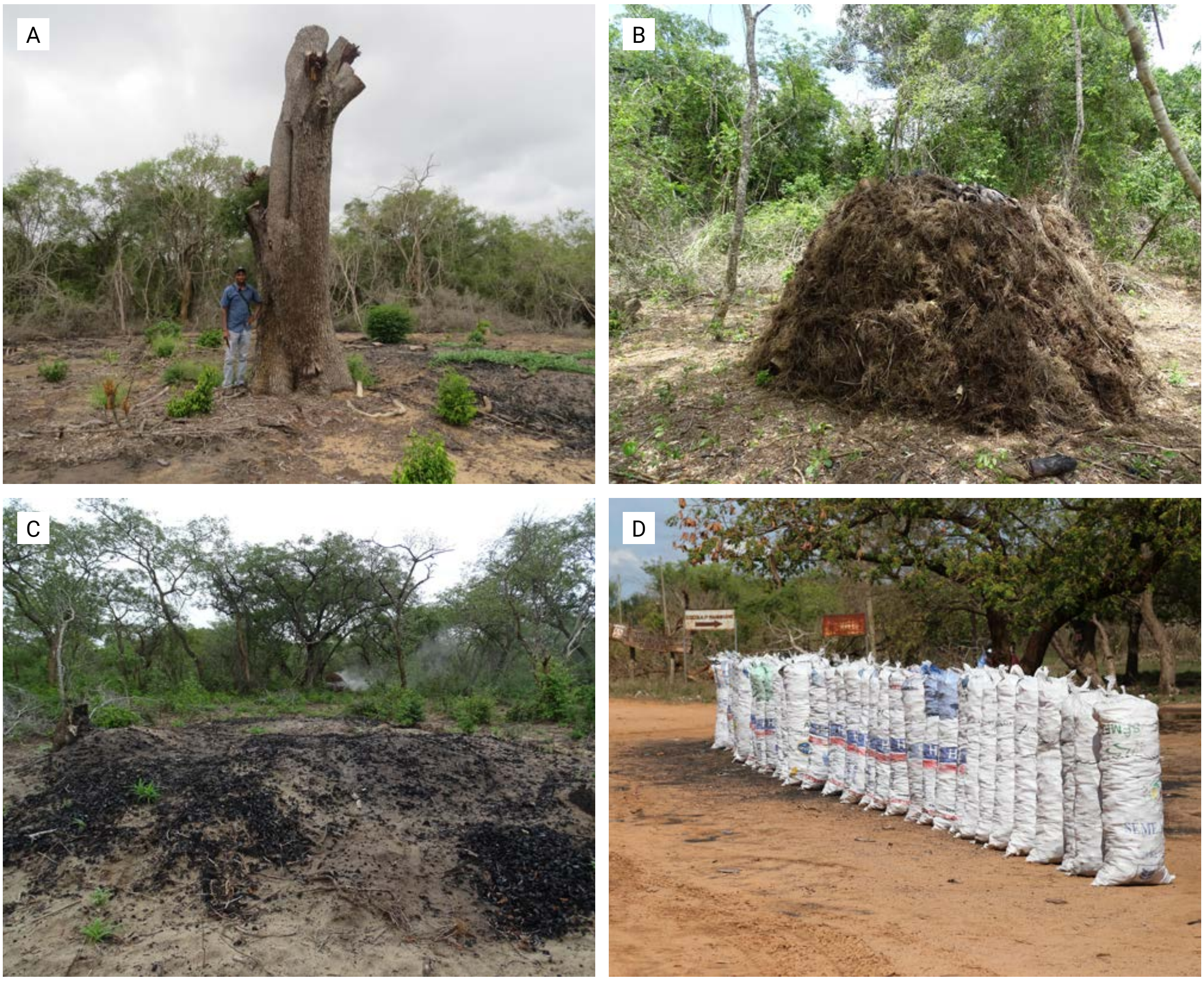

Figure 4. Photos showing the process of charcoal production and trading around the Licuáti Forest Reserve in southern Mozambique. (A) A large *Newtonia hildebrandtii* harvested for charcoal; (B) a charcoal kiln, comprising piled-up, recently-cut timber, which is then covered with twigs and set alight to produce charcoal; (C) an old charcoal kiln (front) and a burning kiln with smoke (back); and (D) bags of charcoal sold on the road side.

Evidence of the use of other natural resources was also observed, including the harvesting of timber for commercial sales, poles for construction materials, and the removal of bark for dye and medicinal purposes. However, the observed uses for these purposes were far less frequent and on a much smaller scale. Thus, their impact on the vegetation in the LFR is considered relatively minor compared to the impact caused by the removal of trees for the production of charcoal.

Discussion

Pattern of deforestation

Forest cover has been continuously reduced in southern Mozambique in the past 25 years as human pressure on the land and on its natural resources has been growing. The rate of deforestation has been accelerating, especially over the past ten years. Although direct comparison is difficult due to differences in methodology and survey periods, our estimates of past (1990–2001) rates for deforestation of 0.1% per annum for the Core Licuáti Forest Reserve (CLFR), and 0.8% per annum for the study area as a whole, were lower than the deforestation rates calculated for the Maputo province between 1990 and 2002, which were recorded as 1.67% per annum (Sitoe et al. 2012). Recent (2013–2016) estimated rates for deforestation of 1.9% per annum for the CLFR and 2.3% per annum for the study area, however, exceeded those figures.

The pattern of deforestation exhibited considerable spatial variation over time. The distribution and shifts in deforestation hotspots suggest that both social and ecological factors influence this pattern. For example, the proximity to major roads, settlements and distribution of alluvial soil along the rivers affect the pattern of deforestation as does the distribution of tall, emergent trees in the Licuáti Thicket. The effects of the social and ecological factors strongly relate to the key proximate causes of deforestation, especially charcoal production, establishment of settlements and increase in agriculture lands.

A series of accuracy assessments confirms overall good matches in the remote sensing analysis. However, the estimated loss in forest cover might either be overestimated, because this study assumed that little regrowth had occurred during the study period, or underestimated because small scale deforestation and degradation may not be sufficiently detected due to limitations in the spatial resolution of the Landsat imagery used in the analysis.

Drivers of deforestation

Charcoal production is the major driver of deforestation in the broader study area as well as within the CLFR. Large trees have been selectively logged and turned into charcoal on site, and then transported to the cities, such as Maputo and Matola, where many of the households use charcoal as a major source of energy (Puná 2008; Sitoe et al. 2012). Working on the basis that one traditional kiln produces 10–20 bags of charcoal, the volume of charcoal recorded at the roadside alone at one point in time is enough to account for 50–100 kilns (Ellegård et al. 2002; Puná 2008). More serious deforestation in the area near the major roads and at closer proximity to the settlements suggests that accessibility to these major charcoal markets influences the rate and extent of deforestation. Similar patterns have also been observed in other areas in Mozambique (Jansen, Bagnoli & Focacci 2008; Sedano et al. 2016), as charcoal is usually transported to the cities by trucks, often a few hundred kilometres away from the forests where it is produced (Ellegård et al. 2002). On the other hand, the effect of other local uses of natural resources is considered minor. For example, local people who collect firewood for cooking usually do not fell large trees in the process (Cuvilas, Jirjis & Lucas 2010; Ellegård et al. 2002; Sitoe et al. 2012).

Land use/land cover change has occurred mostly at the edges of the forest, especially around the villages, major roads and along the Tembe River. The alluvial clayey soil along the Tembe River is more suitable for agriculture (Siebert et al. 2002; Smith et al. 2008), which probably accounts for why the riverine forest along the Tembe River was the first forested area to be transformed into agricultural land after the ceasefire in 1992. In the CLFR, current land use practices suggest that deforestation due to the establishment of settlements and agricultural lands has been limited to the northwestern part of the reserve. The low agricultural potential of the infertile and water repellent soils of the Licuáti Thicket and Licuáti Forest (Kirkwood 2002; Siebert et al. 2002), may prevent its large-scale conversion to agricultural fields. Land already transformed prior to 1990 was likely used for small scale agriculture, grazing for cattle and housing.

Fires have become more frequent in the study area and could have a significant impact on the vegetation in the CLFR. The results suggest that most of the fires observed were initiated in the process of charcoal production, or during the clearing of land either for agriculture or settlements, and then spread causing further loss of forest cover. However, Licuáti Thicket and Licuáti Forest are characterised by having a relatively narrow margin of bare soil extending a few metres from the edge of the vegetation (Matthews et al. 2001). This naturally occurring bare area acts as a fire break and because of this the CLFR has been less impacted by fire than areas outside of the reserve. The long-term effect of fire on the Licuáti Thicket and Licuáti Forest is still unknown. Fire affects seed germination of certain species in the Licuáti Thicket (Kirkwood 2002), but destructive fires in this vegetation type have also been reported (Izidine 2003; Matthews et al. 2001).

While charcoal production and land use/land cover change directly affect the extent and rate of deforestation, indirect effects may facilitate further degradation and deforestation. For example, to enable the transportation of the charcoal, a network of roads and tracks connect recently opened areas. The creation of road networks leads to the further removal of vegetation, and can facilitate the establishment of an agricultural field along the road (Sitoe et al. 2012). Also, as the distance to the large, target trees increases, second-tier, less profitable remaining trees, which are initially overlooked by producers, can be harvested and even relatively degraded forest may be further cleared (Sitoe et al. 2012). These findings highlight the multiple and inter-related causes of deforestation, while the complex linkages make it difficult to isolate the specific influences of different drivers.

The spatiotemporal patterns of deforestation imply that there is an increasing demand for land and for the income that can be derived from the exploitation of natural resources and further points to the unsustainable practice of deforestation. The charcoal producers now migrate further away from cities and roads than ever before to harvest trees and produce charcoal (Ellegård et al. 2002; Puná 2008), while farmers travel further to clear vegetation to start farming. Many trees in the region grow slowly at rates of only 2–5 mm in diameter per year (Gaugris, Van Rooyen & Bothma 2008; Kirkwood 2002) and once large trees have been harvested, it will take hundreds of years for saplings to grow to the same size. This unsustainable practice will damage the natural resources of the area and may result in a reduction in the supply of necessary products and services for rural livelihoods, such as fuelwood and medicine, from Licuáti Thicket and Licuáti Forest.

As is the case elsewhere in Mozambique (Ryan et al. 2014; Sitoe et al. 2012), these findings emphasise the importance of socio-economic factors as the underlying causes of deforestation in the region. For example, the demand for charcoal has been boosted by a rapidly growing urban population. From the charcoal supplier side, prevailing poverty in the rural areas and lack of employment have encouraged people to become involved in the charcoal business (Puná 2008; Ryan et al. 2014; Sitoe et al. 2012). People returning home after the civil war, coupled with population growth in the rural areas of southern Mozambique, increased anthropogenic pressure on natural resources in the study area. In addition, a lack of effective management, monitoring and law enforcement, together with the weakened influence of traditional leaders on natural resource use, particularly by outsiders, has also had an effect on these dynamics (Izidine et al. 2008).

Future perspectives

The projected population growth in cities and the provinces in southern Mozambique (Instituto Nacional de Estatística 2010) suggests that there will be continuous and intensifying anthropogenic pressure on natural resources in the future. Moreover, the recently completed road upgrade between the Mozambique–South Africa border and Boane through the Licuáti Forest Reserve, and the completion of the bridge over Maputo Bay, may accelerate deforestation in southern Mozambique by providing better market access to the cities. Without an affordable alternative for charcoal for urban households, the waves of deforestation described by Ahrends et al. (2010) for Dar es Salaam are likely to expand south from Maputo into the wider LFR area as well.

Changes in socio-economic conditions in the future will increase anthropogenic impact on the remaining forests, and may further increase the threats to biodiversity and cause the possible deterioration of rural livelihoods. Deforestation will reduce the habitats of several endemic plant species that have strong affinities with thicket vegetation such as *Empogona maputensis, Psydrax fragrantissima* and *Warneckea parvifolia*. As shown in other studies, tall emerging trees play a disproportionately important ecological role in these forests and will disappear as a result of the selective logging of large individuals. For example, pods of *Afzelia quanzensis* are known to be a key food source of mammals (Gathua 2000). If deforestation leads to the depletion of the resources, local people will not only lose the source of income, but access to other forest products such as firewood and medicinal plants will also be affected. The forest is also a sacred site, which, if lost, will also affect the cultural identity and practices of the surrounding communities (Izidine et al. 2008, 2009).

Conclusion

The results suggest that the rate of deforestation in the study area is influenced strongly by outsiders who supply the energy needs of the neighbouring urban areas (especially Maputo) with charcoal produced from trees within the wider Licuáti Forest Reserve (LFR) and increasingly, from the Core Licuáti Forest Reserve itself. To slow this impact there is an urgent need to return control of the LFR resources to the surrounding communities themselves and to those responsible for the wise stewardship of the resources of the reserve. The successful community-based forest management strategies, which have worked so successfully to protect the resources of LFR in the past, should be supported and enhanced. There is also a need for new initiatives, such as the provision of solar and gas-generated sources of energy, particularly in the neighbouring cities, to minimise the need for charcoal itself. To inform this, more ecological and socio-economic studies should be undertaken. These include an evaluation of the role of fire in the dynamics of the Licuáti Thicket and Licuáti Forest vegetation as well as an understanding of the livelihood activities that rely on the production and trade of charcoal. A full assessment of the impact of the charcoal trade on local communities will guide effective, equitable and realistic planning in the region.

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Competing interests

The authors declare that they have no financial or personal relationship(s) that may have inappropriately influenced them in writing this article.

Author's contributions

W.T. collected field data in March 2016, analysed the data and wrote the first draft of the manuscript. H.M. facilitated the study and collected field data in October 2015 and 2016. He also led the interviews with community leaders and co-wrote this section of the manuscript and edited and commented on the entire draft. J.S. supervised the remote sensing component of the study and edited the manuscript with a particular focus on the remote sensing analysis. M.T.H. designed the study and assisted with field data collection in October 2015. He also edited the manuscript and co-wrote or re-wrote some of the text where necessary. All authors gave their approval for the final version to be published.

References

Ahrends, A., Burgess, N.D., Milledge, S.A., Bulling, M.T., Fisher, B., Smart, J.C., Clarke, G.P., Mhoro, B.E. & Lewis, S.L., 2010, 'Predictable waves of sequential forest degradation and biodiversity loss spreading from an African city', *Proceedings of the National Academy of Sciences of the United States of America* 107, 14556–14561. doi: 10.1073/pnas.0914471107.

Alfani, F., Azzarri, C., D'Errico, M. & Molini, V., 2012, 'Poverty in Mozambique: New evidence from recent household surveys', *World Bank Policy Research paper* 6217.

Bandyopadhyay, S., Shyamsundar, P. & Baccini, A., 2011, 'Forests, biomass use and poverty in Malawi', *Ecological Economics* 70, 2461–2471. doi: 10.1016/j.ecolecon.2011.08.003.

Burgess, N.D., Malugu, I., Sumbi, P., Kashindye, A., Kijazi, A., Tabor, K., Mbilinyi, B., Kashaigili, J., Wright, T.M., Gereau, R.E., Coad, L., Knights, K., Carr, J., Ahrends, A. & Newham, R.L., 2017, 'Two decades of change in state, pressure and conservation responses in the coastal forest biodiversity hotspot of Tanzania', *Oryx* 51, 77–86. doi:10.1017/S003060531500099X.

Cavendish, W., 2000, 'Empirical regularities in the poverty-environment relationship of rural households: evidence from Zimbabwe', *World Development* 28, 1979–2003. doi: 10.1016/S0305-750X(00)00066-8.

Cuvilas, C.A., Jirjis, R. & Lucas, C., 2010, 'Energy situation in Mozambique: A review', *Renewable and Sustainable Energy Reviews* 14, 2139–2146. doi: 10.1016/j.rser.2010.02.002.

DeFries, R.S., Rudel, T., Uriarte, M. & Hansen, M., 2010, 'Deforestation driven by urban population growth and agricultural trade in the twenty-first century', *Nature Geoscience* 3, 178–181. doi: 10.1038/ngeo756.

Direcção Nacional de Estudos e Análise de Políticas (DNEAP), 2010, '*Poverty and wellbeing in Mozambique: Third national poverty assessment*', Ministry of Planning and Development, Maputo, Mozambique.

Ellegård, A., Chidumayo, E., Malimbwi, R., Pereira, C. & Voss, A., 2002, '*Charcoal potential in southern Africa CHAPOSA (Final Report)*', Stockholm Environment Institute, Stockholm, Sweden.

Gathua, M., 2000, 'The effects of primates and squirrels on seed survival of a canopy tree, *Afzelia quanzensis*, in Arabuko-Sokoke Forest, Kenya', *Biotropica* 32, 127–132. doi: 10.1111/j.1744-7429.2000.tb00455.x.

Gaugris, J.Y. & Van Rooyen, M.W., 2008, 'A spatial and temporal analysis of Sand Forest tree assemblages in Maputaland, South Africa', *South African Journal of Wildlife Research* 38, 171–184. doi: 10.3957/0379-4369-38.2.171.

Gaugris, J.Y., Van Rooyen, M.W. & Bothma, J. du P., 2008, 'Growth rate of selected woody species in northern Maputaland, KwaZulu-Natal, South Africa', *South African Journal of Botany* 74, 85–92. doi: 10.1016/j.sajb.2007.09.001.

Geist, H.J. & Lambin, E.F., 2002, 'Proximate causes and underlying driving forces of tropical deforestation: Tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations', *Bioscience* 52, 143–150. doi: 10.1641/0006-3568(2002)052[0143:PCAUDF]2.0.CO;2.

Green, J.M.H., Larrosa, C., Burgess, N.D., Balmford, A., Johnston, A., Mbilinyi, B.P., Platts, P.J. & Coad, L., 2013, 'Deforestation in an African biodiversity hotspot: Extent, variation and the effectiveness of protected areas', *Biological Conservation* 164, 62–72. doi: 10.1016/j.biocon.2013.04.016.

Hansen, M.C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. & Townshend, J.R.G., 2013, 'High-resolution global maps of 21st-century forest cover change', *Science* 342, 850–853. doi: 10.1126/science.1244693.

Hosonuma, N., Herold, M., De Sy, V., De Fries, R.S., Brockhaus, M., Verchot, L., Angelsen, A. & Romijn, E., 2012, 'An assessment of deforestation and forest degradation drivers in developing countries', *Environmental Research Letters* 7, 44009. doi: 10.1088/1748-9326/7/4/044009.

Instituto Nacional de Estatística, 2010, *Projecções da População 2007–2040*, viewed 24 November 2016 from http://www.ine.gov.mz/.

Izidine, S.A. 2003, 'Licuáti Forest Reserve, Mozambique: Flora, utilization and conservation', MSc thesis, Dept. of Wildlife Management, University of Pretoria, South Africa.

Izidine, S., Siebert, S. & Van Wyk, B., 2003, 'Maputaland's Licuáti forest and thicket', *Veld & Flora* 89, June, pp. 56–61.

Izidine, S.A., Siebert, S.J., Van Wyk, A.E. & Zobolo, A.M., 2008, 'Taboo and political authority in conservation policy: A case study of the Licuáti Forest in Maputaland, Mozambique', *Journal for the Scientific Study of Religion* 2, 373–390. doi: 10.1558/jsrnc.v2i3.373.

Izidine, S., Siebert, S., Van Wyk, A.E. & Zobolo, A.M., 2009, 'Threats to Ronga custodianship of a sacred grove in southern Mozambique', *African Journal of Indigenous Knowledge Systems* 7, 182–197. doi: 10.4314/indilinga.v7i2.26435.

Jansen, L.J.M., Bagnoli, M. & Focacci, M., 2008, 'Analysis of land-cover/use change dynamics in Manica Province in Mozambique in a period of transition (1990–2004)', *Forest Ecology and Management* 254, 308–326. doi: 10.1016/j.foreco.2007.08.017.

Kirkwood, D., 2002, 'Floristics and dynamics of Sand Forest, a subtropical dry forest type in South Africa', PhD thesis, Dept. of Botany, University of Cape Town, South Africa.

Kleemann, J., Baysal, G., Bulley, H.N. & Fürst, C., 2017, 'Assessing driving forces of land use and land cover change by a mixed-method approach in north-eastern Ghana, West Africa', *Journal of Environmental Management* 196, 411-442. doi: 10.1016/j.jenvman.2017.01.053.

Kloppers, R.J. 2001, 'The utilisation of natural resources in the Matutuine district of southern Mozambique: implications for transfrontier conservation', MA thesis, Department of Anthropology, University of Pretoria, South Africa.

Matthews, W.S., Van Wyk, A.E., Van Rooyen, N. & Botha, G.A., 2001, 'Vegetation of the Tembe Elephant Park, Maputaland, South Africa', *South African Journal of Botany* 67, 573–594. doi: 10.1016/S0254-6299(15)31188-1.

Mayaux, P., Pekel, J-F., Desclée, B., Donnay, F., Lupi, A., Achard, F., Clerici M., Bodart, C., Brink, A., Nasi, R. & Belward, A., 2013, 'State and evolution of the African rainforests between 1990 and 2010', *Philosophical Transactions of the Royal Society B Biological Sciences* 368, 20120300–20120300. doi: 10.1098/rstb.2012.0300.

McGregor, J., 1998, 'Violence and social change in a border economy: war in the Maputo hinterland, 1984–1992', *Journal of Southern African Studies* 24, 37–60. doi: 10.1080/03057079808708566.

Millennium Ecosystem Assessment, 2005, 'Ecosystems and human well-being: Synthesis', Washington, DC. USA.

Puná, N.H., 2008, 'Charcoal supply chain study in Mozambique', in R. Kwaschik (ed), *Conference on charcoal and communities in Africa, proceedings,* Maputo, Mozambique, June 16-18, 2008, pp. 62–76.

Puyravaud, J-P., 2003, 'Standardizing the calculation of the annual rate of deforestation', *Forest Ecology and Management* 177, 593–596. doi: 10.1016/S0378-1127(02)00335-3.

R Core Team, 2014, 'R: a language and environment for statistical computing', R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/.

Rudel, T.K., 2013, 'The national determinants of deforestation in sub-Saharan Africa', *Philosophical Transactions of the Royal Society B Biological Sciences* 368, 20120405–20120405. doi: 10.1098/rstb.2012.0405.

Rudel, T.K., DeFries, R., Asner, G.P. & Laurance, W.F., 2009, 'Changing drivers of deforestation and new opportunities for conservation', *Conservation Biology* 23, 1396–1405. doi: 10.1111/j.1523-1739.2009.01332.x.

Ryan, C.M., Berry, N.J. & Joshi, N., 2014, 'Quantifying the causes of deforestation and degradation and creating transparent REDD+ baselines: A method and case study from central Mozambique', *Applied Geography* 53, 45–54. doi: 10.1016/j.apgeog.2014.05.014.

Ryan, C.M., Pritchard, R., McNicol, I., Owen, M., Fisher, J.A. & Lehmann, C., 2016, 'Ecosystem services from southern African woodlands and their future under global change', *Philosophical Transactions of the Royal Society B Biological Sciences* 371, 20150312. doi: 10.1098/rstb.2015.0312.

Sedano, F., Silva, J.A., Machoco, R., Meque, C.H., Sitoe, A., Ribeiro, N., Anderson, K., Ombe, Z.A., Baule, S.H. & Tucker, C.J., 2016, 'The impact of charcoal production on forest degradation: a case study in Tete, Mozambique', *Environmental Research Letters* 11, 094020. doi: 10.1088/1748-9326/11/9/094020.

Siebert, S., Bandeira, S., Burrows, J. & Winter, P., 2002, 'SABONET Southern Mozambique expedition 2001', *SABONET News* 7, 6–18.

Sitoe, A., Salomão, A. & Wertz-Kanounnikoff, S., 2012, 'The context of REDD+ in Mozambique: drivers, agents, and institutions', CIFOR, Bogor.

Smith, R.J., Easton, J., Nhancale, B.A., Armstrong, A.J., Culverwell, J., Dlamini, S.K., Goodman, P.S., Loffler, L., Matthews, W.S., Monadjem, A., Mulqueeny, C., Ngwenya, P., Ntumi, C.P., Soto, B. & Leader-Williams, N., 2008, 'Designing a transfrontier conservation landscape for the Maputaland centre of endemism using biodiversity, economic and threat data', *Biological Conservation* 141, 2127–2138. doi: 10.1016/j.biocon.2008.06.010.

Soto, B., Munthali, S.M. & Breen, C., 2001, 'Perception of the forestry and wildlife policy by the local communities living in the Maputo elephant reserve, Mozambique', *Biodiversity and Conservation* 10, 1723–1738. doi: 10.1023/A:1012005620906.

Steenkamp, Y., Van Wyk, B., Victor, J., Hoare, D., Smith, G., Dold, A. & Cowling, R.M., 2004, 'Maputaland–Pondoland–Albany', in R.A. Mittermeier, P.R. Gil, M. Hoffman, J. Pilgrim, T. Brooks, C.G. Mittermeier, J. Lamoreux, & G.A.B. Da Fonseca (eds.) *Hotspots revisited*, pp. 219-228, The University of Chicago Press, Chicago.

Tredennick, A.T. & Hanan, N.P., 2015, 'Effects of tree harvest on the stable-state dynamics of savanna and forest', *American Naturalist* 185, E153-E165. doi: 10.1086/680475.

Turner, B.L., Lambin, E.F. & Reenberg, A., 2007, 'The emergence of land change science for global environmental change and sustainability', *Proceedings of the National Academy of Sciences of the United States of America* 104, 20666–20671. doi: 10.1073/pnas.0704119104.

Van Wyk, A.E., 1996, 'Biodiversity of the Maputaland Centre, in L.J.G. van der Maesen, X.M. van der Burgt & J.M. van Medenbach de Rooy (eds.), *The biodiversity of African plants: XIVth AETFAT Congress proceedings,* Wageningen, Netherlands, 22-27 August 1994, pp. 198–207.

Wiesmann, D. & Quinn, D., 2016, *Rasclass: supervised raster image classification*, viewed 28 September 2016 from https://CRAN.R-project.org/package=rasclass.

Woollen, E., Ryan, C.M., Baumert, S., Vollmer, F., Grundy, I., Fisher, J., Fernando, J., Luz, A., Ribeiro, N. & Lisboa, S.N., 2016, 'Charcoal production in the Mopane woodlands of Mozambique: what are the trade-offs with other ecosystem services?', *Philosophical Transactions of the Royal Society B Biological Sciences* 371(1703), 20150315. doi: 0.1098/rstb.2015.0315.

Zulu, L.C. & Richardson, R.B., 2013, 'Charcoal, livelihoods, and poverty reduction: Evidence from sub-Saharan Africa', *Energy for Sustainable Development* 17, 127–137. doi: 10.1016/j.esd.2012.07.007.

Supplementary information

Calculation of deforestation rate

To calculate *r*, mean annual rate of change of forest cover, we used the following formula after Puyavaud (2003)

$$r = \frac{1}{t_2 - t_1} \times \ln \frac{A_2}{A_1}$$

where A1 and A2 are the forest cover at time t1 and t2, respectively.

Landsat images used in the study

SI Table 1. Details of the Landsat images used in this study

Sensor	Date	ID
Landsat 5 TM	1990 June 02	LT51670781990153JSA00
Landsat 7 ETM+	2001 May 08	LE71670782001127SGS00
Landsat 5 TM	2007 April 30	LT51670782007120JSA00
Landsat 8 OLI	2013 May 16	LC81670782013136LGN01
Landsat 8 OLI	2016 May 24	LC81670782016145LGN00

Accuracy assessment

SI Table 2. Confusion matrix of direct classification using a support vector machine algorithm (NF: persistent non forest, FL1990–2001: forest loss 1990–2001, FL2001–2007: forest loss 2001–2007, FL2007–2013: forest loss 2007–2013, FL2013–2016: forest loss 2013–2016, PF: persistent forest)

		Validate dataset						Row total	User's accuracy
		NF	FL1990–2001	FL2001–2007	FL2007–2013	FL2013–2016	PF		
Mapped classification	NF	98	4	0	0	0	0	102	96.1%
	FL1990–2001	1	95	0	0	0	0	96	99.0%
	FL2001–2007	1	1	97	1	0	0	100	97.0%
	FL2007–2013	0	0	3	99	0	0	102	97.1%
	FL2013–2016	0	0	0	0	100	0	100	100.0%
	PF	0	0	0	0	0	100	100	100.0%
Column total		100	100	100	100	100	100	600	-
Producer's accuracy		98.0%	95.0%	97.0%	99.0%	100.0%	100.0%	-	-

Overall accuracy: 98.2% Kappa coefficient: 0.98

SI Table 3. Confusion matrix of independent accuracy assessment comparing Google Earth imagery with the extent of forest estimated by a support vector machine algorithm in 2013

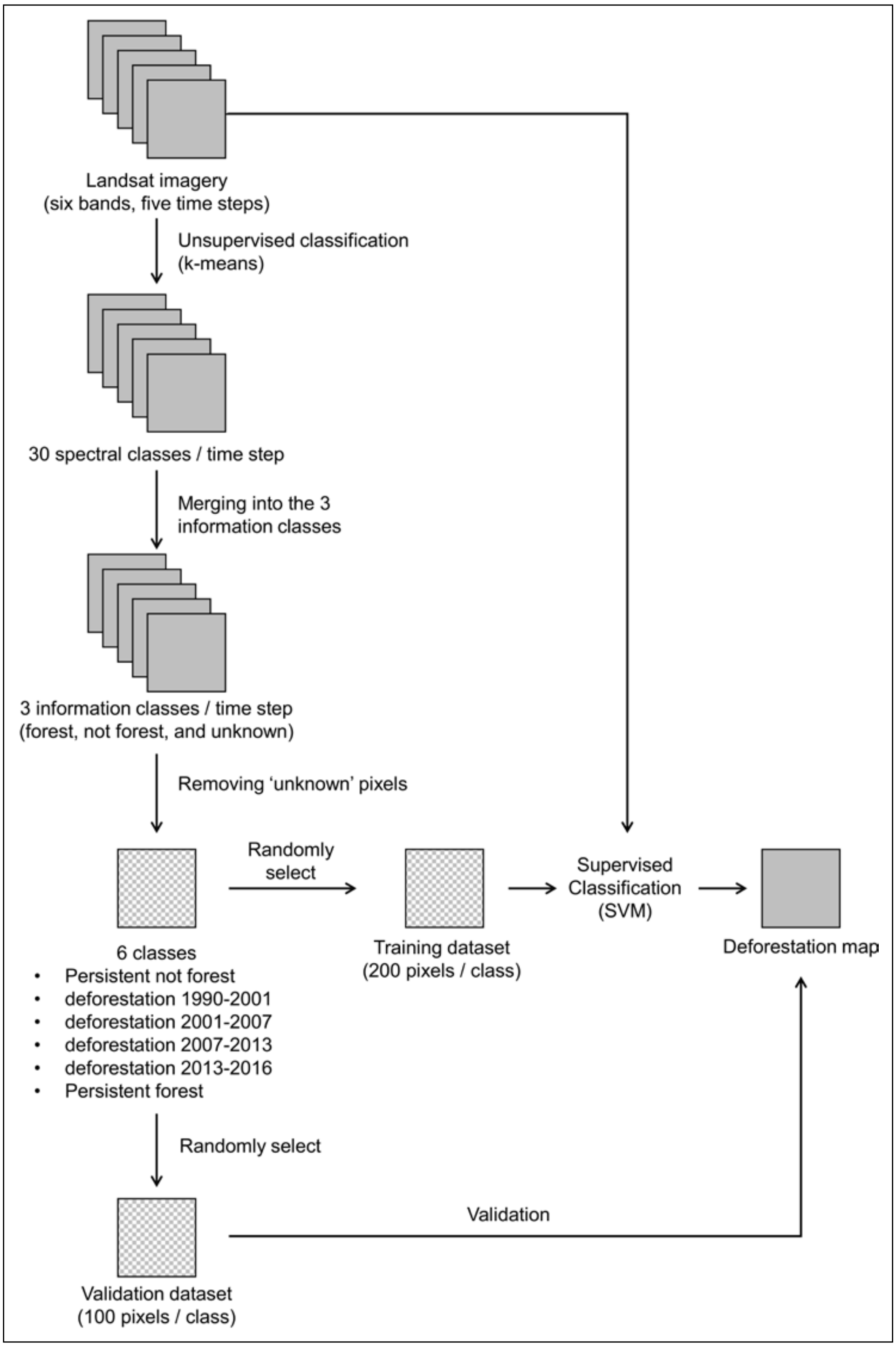
		Validate dataset		Totals	User's accuracy
		Non forest	Forest		
Mapped classification	Non forest	43	7	50	86.0%
	Forest	7	43	50	86.0%
Column total		50	50	100	
Producer's accuracy		86.0%	86.0%		

Overall accuracy: 86.0% Kappa coefficient: 0.72

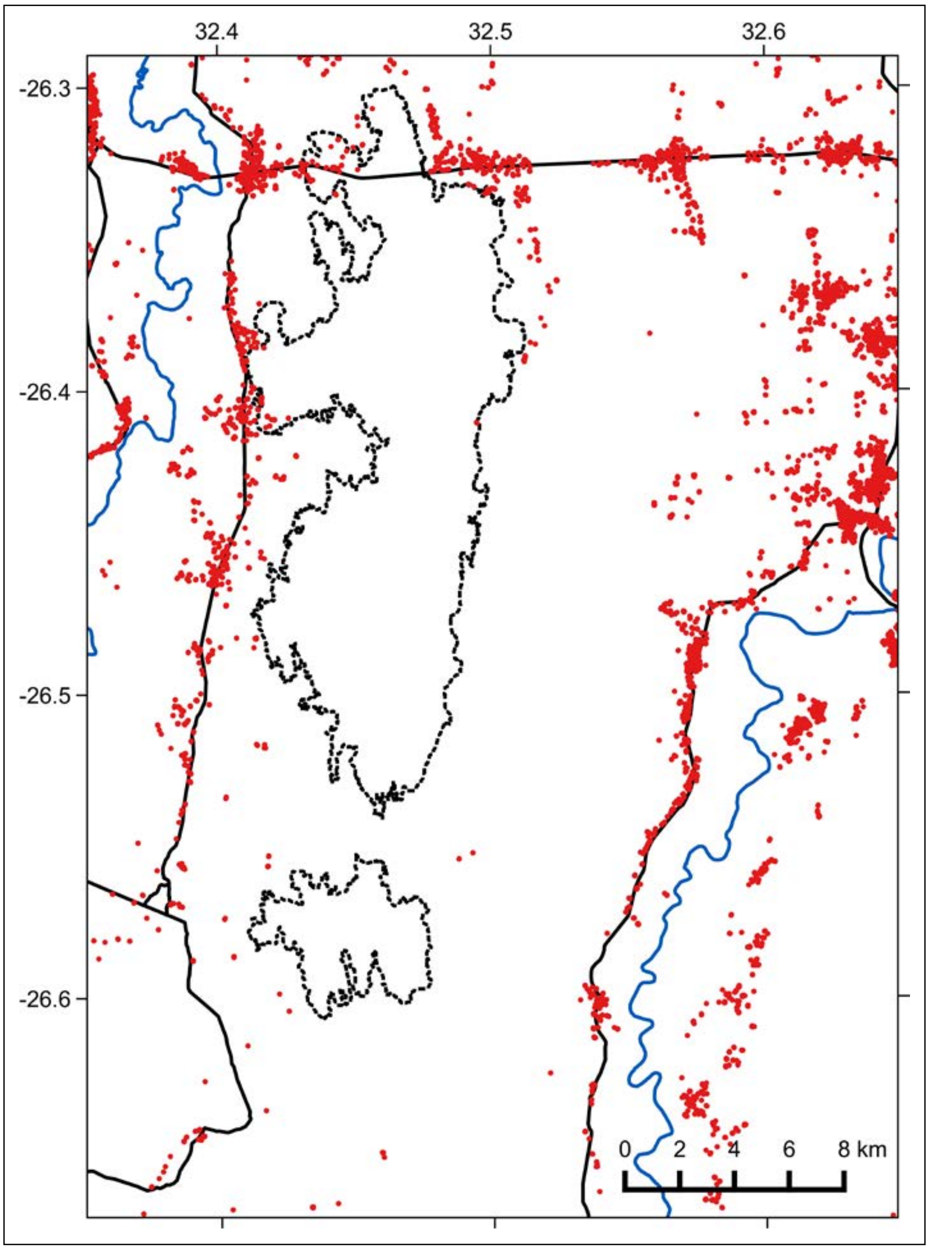
SI Table 4. Confusion matrix of independent accuracy assessment comparing Google Earth imagery and Sentinel-2 with the extent of forest estimated by a support vector machine algorithm in 2016

		Validate dataset		Totals	User's accuracy
		Non forest	Forest		
Mapped classification	Non forest	47	3	50	94.0%
	Forest	6	44	50	88.0%
Column total		53	47	100	
Producer's accuracy		88.7%	93.6%		

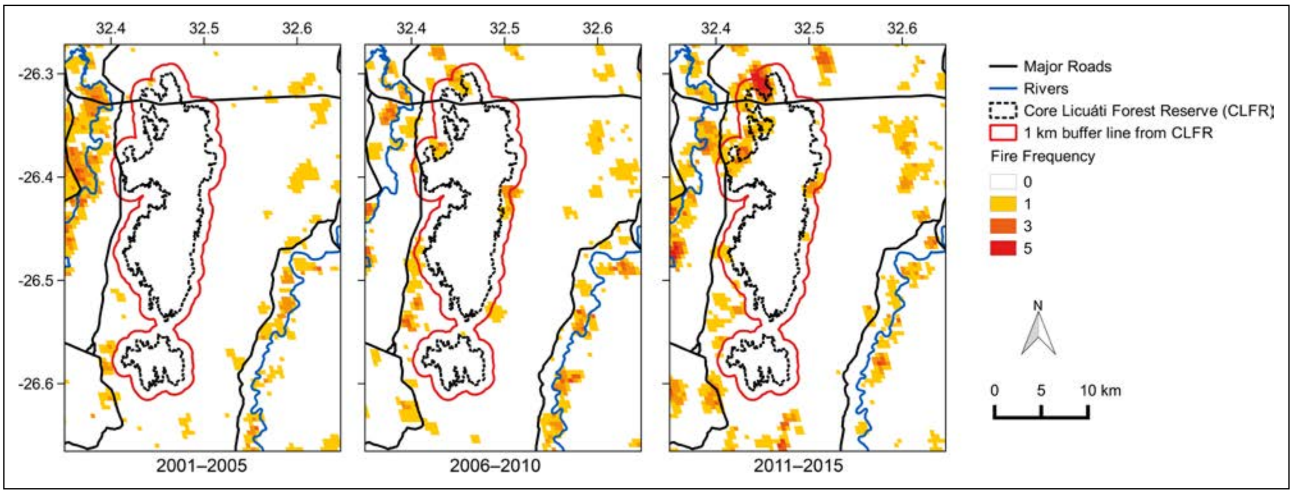
Overall accuracy: 91.0% Kappa coefficient: 0.82



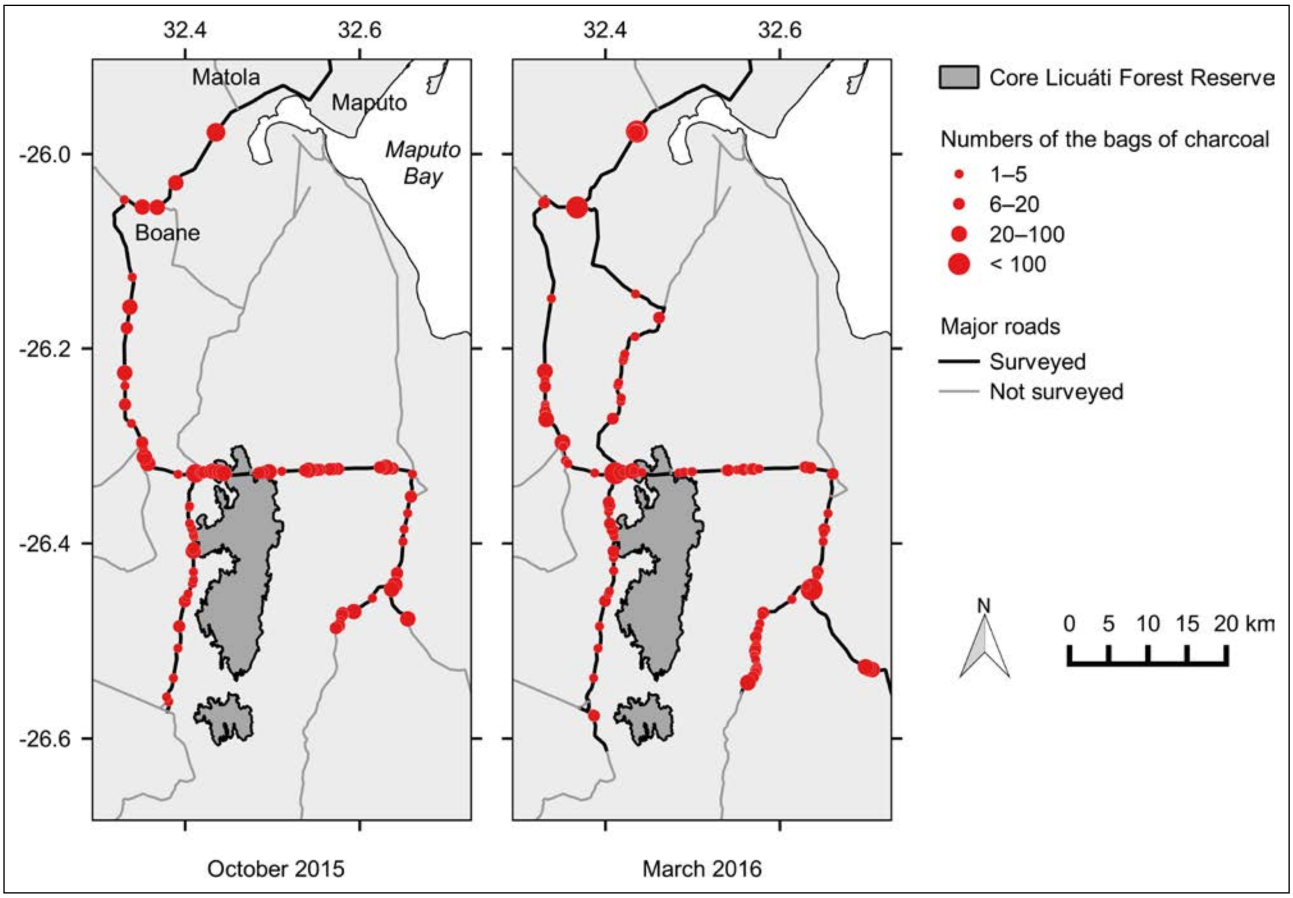
SI Figure 1. Flowchart of deforestation analysis used in this study. Each grey square represents one image at one time step, while each dotted square represents selected pixels in a raster file.



SI Figure 2. The location of human settlements in the wider study area in southern Mozambique. Dotted lines indicate the Core Licuáti Forest Reserve, while red dots indicate the distribution of houses identified by high resolution Google Earth imagery taken over the period August to September 2015.



SI Figure 3. Fire history map of the study area in southern Mozambique estimated by MODIS burned area product (MCD45A1) in three time steps between 2001 and 2015. The Core Licuáti Forest Reserve is outlined in black as is a 1 km buffer area (red line) around the CLFR.



SI Figure 4. Distribution of charcoal bags sold along the road side in southern Mozambique in October 2015 (left) and March 2016 (right).

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Environmental factors that influence species diversity of floodplain plant communities in different flooding phases in the Okavango Delta, Botswana

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Background and objectives: Species composition and distribution in seasonal floodplain plant communities are influenced by variation in flooding. However, the influence of intra-flooding variation phases on the diversity of seasonal floodplain plant communities has not been studied in the Okavango Delta. The objective of this study was to investigate environmental factors that influence species composition and distribution of seasonal floodplain communities before and after flooding. It was hypothesised that environmental factors that influence the species composition and distribution in seasonal floodplain communities will vary with intra-flooding seasons.

Methods: Flooding depth was measured in May (before flooding) and September (flood recession/after flooding) in forty 25 m^2 plots. Flooding duration was recorded as the number of weeks in which the plots were inundated. The soil was sampled before and after floods and analysed for pH, extractable P, K, Mg, Ca and Na. Plant identification and estimation of percentage cover were done in the 25 m^2 plots in which environmental variables were sampled. The relationship between environmental variables and seasonal floodplain plant community composition and distribution was sought using Non-metric Multi-dimensional Scaling. Paired *Student's t* test was used to compare the means of environmental variables before and after flooding.

Results: Factors that influenced the distribution of species before flooding were Na, K, water depth and flooding duration. After flooding, the factors that influenced species composition and distribution were K, Na, Mg, pH, water depth and flooding duration.

Conclusion: These results suggest that during flooding K and Mg are deposited in the floodplains due to lateral water flow. Our results also suggest that any water abstraction from the Okavango River Basin should take into consideration the importance of flooding duration and depth in sustaining species composition and distribution of seasonal floodplain plant communities so that such developments do not disturb the ecological functioning of the Delta.

Key words: Environmental factors, flooding, flood plain, Okavango Delta and vegetation.

Introduction

Seasonal floodplain plant communities are an important component of the ecology of the wetland ecosystems. They are dynamic and heterogeneous (Benstead et al. 1997; Toogood et al. 2008) with their species composition and distribution influenced by the variation in seasonal flooding, which is a function of topography (Merritt et al. 2009; Oliveria-Filho et al. 1994; Toogood, Joyce & Waite 2008). Lowly elevated floodplains usually have higher water levels and longer flooding duration than highly elevated ones (Growing, Spoor & Mountford 1998). This results in the lowly elevated floodplains being dominated by flood tolerant species such as *Hydrilla verticillata* (L.f.) Royle, which grows well when fully submerged and *Typha angustifolia* L. (Cronk & Fennessy 2000). Highly elevated floodplains are dominated by flood intolerant species such as *Chrysopogon nigritanus* (Benth.) Veldkamp, *Sporobolus spicatus* (Vahl) Kunth and *Imperata cylindrica* (L.) Raeusch. (Bonyongo, Bredenkamp & Veenendaal 2000).

The influence of flooding on plants is reflected in seasonal floodplain vegetation community composition and distribution (Oliveria-Filho et al. 1994). Each plant species is morphologically and physiologically adapted to a range of flooding depth and duration conditions (Cronk & Fennessy 2001; Edwards & Kollman 2002; Merritt et al. 2009). Morphological adaptation to flooding such as growth of hytrophied lenticels, aerenchyma tissue and adventitious roots enhance oxygen transport in plants, enabling them to survive flooding conditions (Kozlowski 1984). Physiological adaptations to flooding include germination inhibition, glycolysis and ethylene production (Naiman & Decamps 1997).

The influence of environmental factors that influence the plant species composition and distribution in seasonal floodplain communities has been studied in several wetland ecosystems such as the Pantanal (Pinder & Rosso 1998; Ponce & Da Cunha 1993), the Amazon (Junk 1997; Parolin et al. 2006), the Everglades (Davis & Ogden 1993), the Kafue (Rees 1978), including the Okavango Delta (Biggs 1976; Bonyongo et al. 2000; Ellery, Ellery & McCarthy 1993; Ellery & Tacheba 2003; Murray-Hudson 2009; Smith 1976; Tsheboeng, Bonyongo & Murray-Hudson 2014). In these wetlands flooding has been identified as the primary driver of the

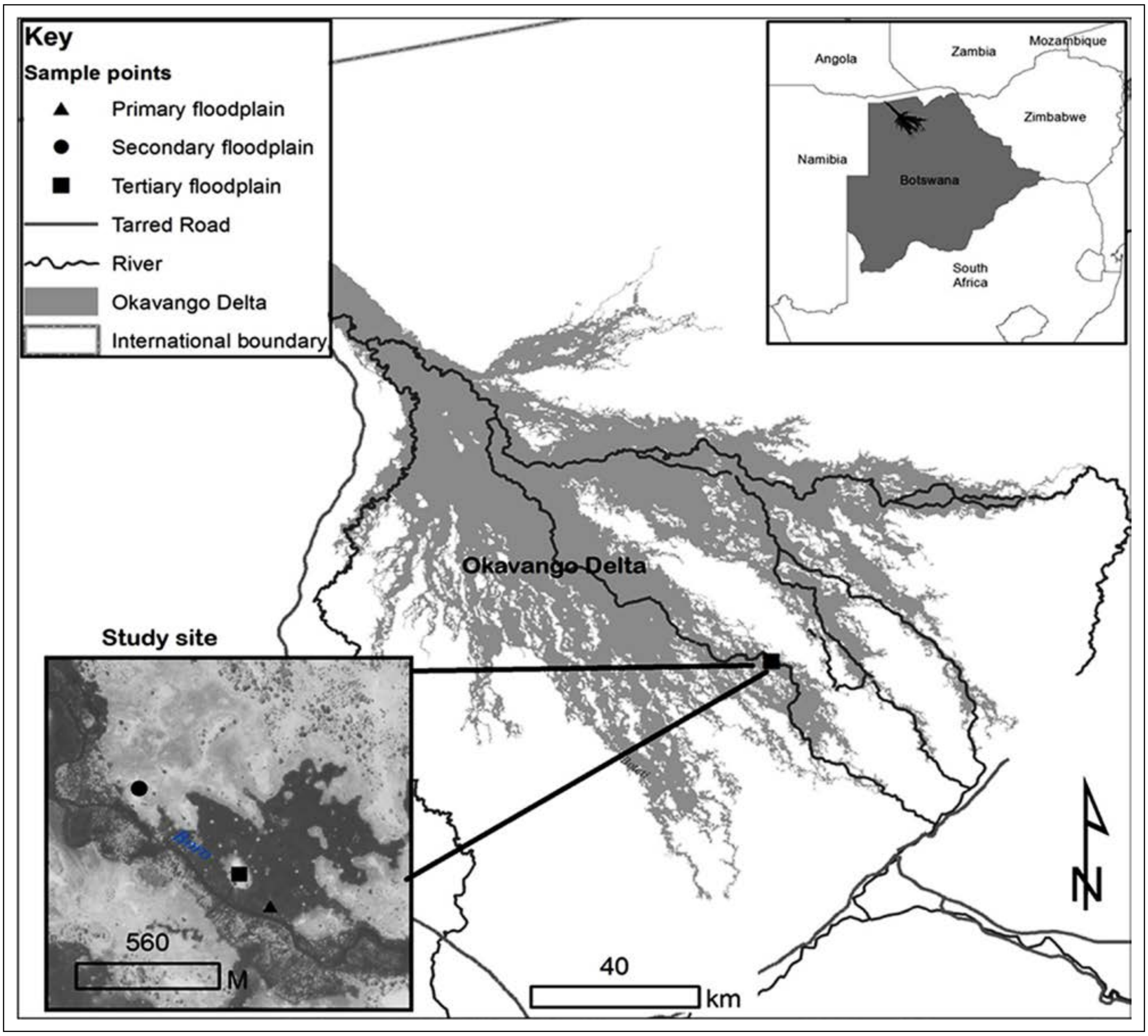

Figure 1. Map showing location of Nxaraga where the study was conducted. From Tsheboeng et al. (2014).

Table 1: Hydrological regions in the Okavango Delta

Region	Area covered (km²)	Hydroperiod characteristics	Common plant species
Permanent swamp	2 500	Flooded all year round	*Phragmites australis* (Cav.) Trin. ex Steud, *Cyperus papyrus* L and *P. mauritianus* Kunth
Primary floodplain	690	Flooded every year for 6 to 8 months. May be flooded for 12 months during high flood	*Cyperus articulatus* L, *Schoenoplectus corymbosus* (Roth ex Roem. & Schult.) J.Raynal and *Miscanthus junceus* (Stapf) Pilg.
Secondary floodplain	1 347	Flooded up to 5 months	*Panicum repens* L, *Setaria sphacelata* (Schumach.) Stapf & C.E.Hubb. ex Moss and *Eragrostis inamoena* K.Schum.
Tertiary floodplain	7 100	Variable hydroperiod	*Sporobolus spicatus* (Vahl) Kunth and *Cynodon dactylon* (L) Pers.

Adapted from Gumbricht et al. (2004).

plant species composition and distribution in seasonal floodplain communities (Pinder & Rosso 1998; Ponce & Cunha 1993; De Oliveira et al. 2014).

In the Okavango Delta, previous studies have also attributed plant species composition and distribution in seasonal floodplain communities to flooding depth (Bonyongo et al. 2000; Murray-Hudson 2009). It has also been found that other environmental factors, including distance from the water source, ground water electrical conductivity, pH, soil chemistry (Ellery et al. 1993), timing of inundation, soil salinity, and nutrient and sediment supply (Ellery & Tacheba 2003) were responsible for controlling the species composition and distribution in seasonal floodplain plant communities. However, these conclusions were based on studies conducted during low flood. As a result they do not provide information on significant environmental factors determining seasonal floodplain vegetation community composition and distribution during a high flood.

Furthermore, the previous studies on the species composition and distribution of seasonal floodplain communities did not consider the intra-flooding variation phases of middle of rainfall season, before flooding and after flooding. To address this, the current study aimed to investigate environmental factors determining seasonal floodplain vegetation community composition and distribution before flooding and after flooding during a high flood year in the Okavango Delta. It was hypothesised that environmental factors that influence the species composition and distribution in seasonal floodplain communities in the Okavango Delta will vary with flooding phases.

Materials and methods

Study site

This study was conducted in the Okavango Delta in the Nxaraga lagoon area (Figure 1).

The Okavango Delta is fed by local rainfall and seasonal floods from the Angolan highlands (Gumbricht, McCarthy & McCarthy 2004), which are asynchronous (McCarthy & Ellery 1998). The total flooded area in the Okavango Delta ranges between 4 000 km^2 and 13 000 km^2 (McCarthy 2006). This variation is influenced by the seasonal variation in the local rainfall and flood discharge (Gumbricht et al. 2004). The Delta receives the lowest inflow between September and November and receives the highest inflow between March and April (McCarthy & Ellery 1998). Mean maximum rainfall in the Okavango Delta ranges between 300 and 550 mm/year (Wilson & Dincer 1976). The annual mean flood discharge ranges between 6.0×10^9 m^3 and 16.4×10^9 m^3 (Gumbricht et al. 2004) of which approximately 96% is lost through evapotranspiration while 2% is lost through infiltration (Wilson & Dincer 1976). Another 2% is lost as outflow through Thamalakane River (Wilson & Dincer 1976).

There are three hydrological regions in the Delta namely: permanent swamp, seasonally flooded floodplains (primary and secondary floodplains) and occasionally flooded floodplains (tertiary floodplains) (Gumbricht et al. 2004). Each hydrological region is characterised by a particular range of hydroperiod (Wolski et al. 2006) and associated vegetation communities (Bonyongo et al. 2000) (Table 1).

The Delta experiences mean monthly maximum and minimum summer temperatures ranging from 30.5°C to 40°C and 14.8°C to 19.2°C respectively (Ellery 1991). During winter mean monthly maximum temperature ranges from 25.3°C to 28.7°C and minimum temperature ranges from 7.0°C to 10.0°C (Ellery 1991).

Hydrology and vegetation sampling

Flooding depth (in centimetres) was measured using a calibrated 2 m PVC pipe in mid-May 2010 (flood propagation) and end of September 2010 (flood recession).

Table 2: Modified Braun-Blanquet percentage cover/abundance scale

Level	Description
5	75–100% plot cover
4	50–75% plot cover
3	25–50% plot cover
2B	15–25% plot cover
2A	5–15% plot cover
2M	1–5% plot cover, over 50 individuals
1	1–5% plot cover, 6–50 individuals
+	Less than 1% plot cover, 3–5 individuals
R	Less than 1% plot cover, 1–2 individuals

It was measured in 25 m^2 permanent plots in each of the hydrological regions (Table 1) per flooding season (before flooding and flood recession) where vegetation and soil were also sampled. A total of 40 plots were sampled. The soils were collected from the centre of each permanent plot using a soil auger at a maximum depth of 30 m. Flooding duration was recorded as the number of weeks in which the permanent plots remained inundated.

Vegetation was sampled from randomly selected plots during the same period when flooding parameters were sampled. The plots were placed in different floodplains of primary (10 plots), secondary (15 plots) and tertiary (15 plots) (Bonyongo et al. 2000; Gumbricht et al. 2004; Table 1). The dimension for the vegetation plots were 5 × 5 m. This is the minimal sampling plot area that was determined by Bonyongo et al. (2000) for sampling the seasonal floodplain vegetation in this study area. In each plot, plant percentage cover was estimated following the modified method by Braun-Blanquet (Mueller-Dombois & Ellenberg 1974). The Braun-Blanquet method was used to estimate plant species percentage cover using an ordinal scale (Table 2). Percentage cover was estimated for the emergent plant species only.

Measured environmental variables

The soil was sampled before and after floods and analysed for pH, extractable P, K, Mg, Ca and Na at the University of Botswana Okavango Research Institute Laboratory. They were collected at a depth of 30 cm from the same 25 m^2 plots where plant species were sampled. A detailed analysis of soil samples is given in Tsheboeng et al. (2014).

Statistical data analysis

The relationship between environmental variables and seasonal floodplain vegetation community composition and distribution was sought using Non-metric Multidimensional Scaling (NMS) (Kruskal 1964; Mather 1976) in PC-ORD version 6. NMS was used to relate soil nutrients, flooding depth and duration to vegetation community composition and distribution. The following parameters were used in the NMS: Sorensen distance measure, random starting configuration, 50 runs with real data, 3 dimensions and 100 iterations. Monte Carlo test was performed with 20 runs. The total number of iterations was 70 in the final solution. NMS does not require assumptions about the underlying distribution of vegetation communities. It does not assume linear relationships between environmental variables (McCune & Grace 2000), hence it was suitable for analysing the relationship between seasonal floodplain vegetation communities and environmental variables in the Okavango Delta. The paired *Student's t* test was used to compare means of environmental variables before and after flooding.

Results

Flooding depth was significantly ($p < 0.05$) higher in all hydrological zones after flooding than before flooding (Table 3). The content of K, Ca and flooding duration were significantly higher ($p < 0.05$) before than after floods (Table 3).

Table 3: Mean (± standard error) soil nutrient content before flooding and after flood recession in seasonal floodplain zones (N = 40)

Environmental variables	Before flooding	After flooding	*p* value
Na	246.92 ± 218.91 mg/kg	177.73 ± 103.29 mg/kg	0.159
Mg	405.87 ± 389.24 mg/kg	297.59 ± 188.0 mg/kg	0.284
K	487.53 ± 367.68 mg/kg	322.05 ± 170.59 mg/kg	0.042*
Ca	1297.30 ± 1173.43 mg/kg	560.94 ± 378.53 mg/kg	0.028*
P	2380.45 ± 546.78 mg/kg	2565.64 ± 723.06 mg/kg	0.488
pH	6.87 ± 0.95	6.74 ± 0.77	0.565
Flooding duration (weeks)	68	54	0.0001*
Mean flooding depth	36.5 ± 15.01 cm	73.65 ± 22.64 cm	0.137

*Significant difference at $p < 0.05$.

Factors that influence floodplain plant community composition and distribution

Before floods factors

NMS ordination showed that before flooding, important factors that influence the distribution of seasonal floodplain communities were Na, K, flooding depth and flooding duration (Figure 2).

Before flooding Na, Mg, K, Ca and pH were negatively correlated with species along Axis 1, but positively correlated to those along Axis 2. Flooding duration and P were negatively correlated with species oriented along Axis 2 while flooding depth was positively correlated to both axes (Table 4 and Figure 2).

After flooding

After flooding the significant factors that influenced the species composition in seasonal floodplain communities

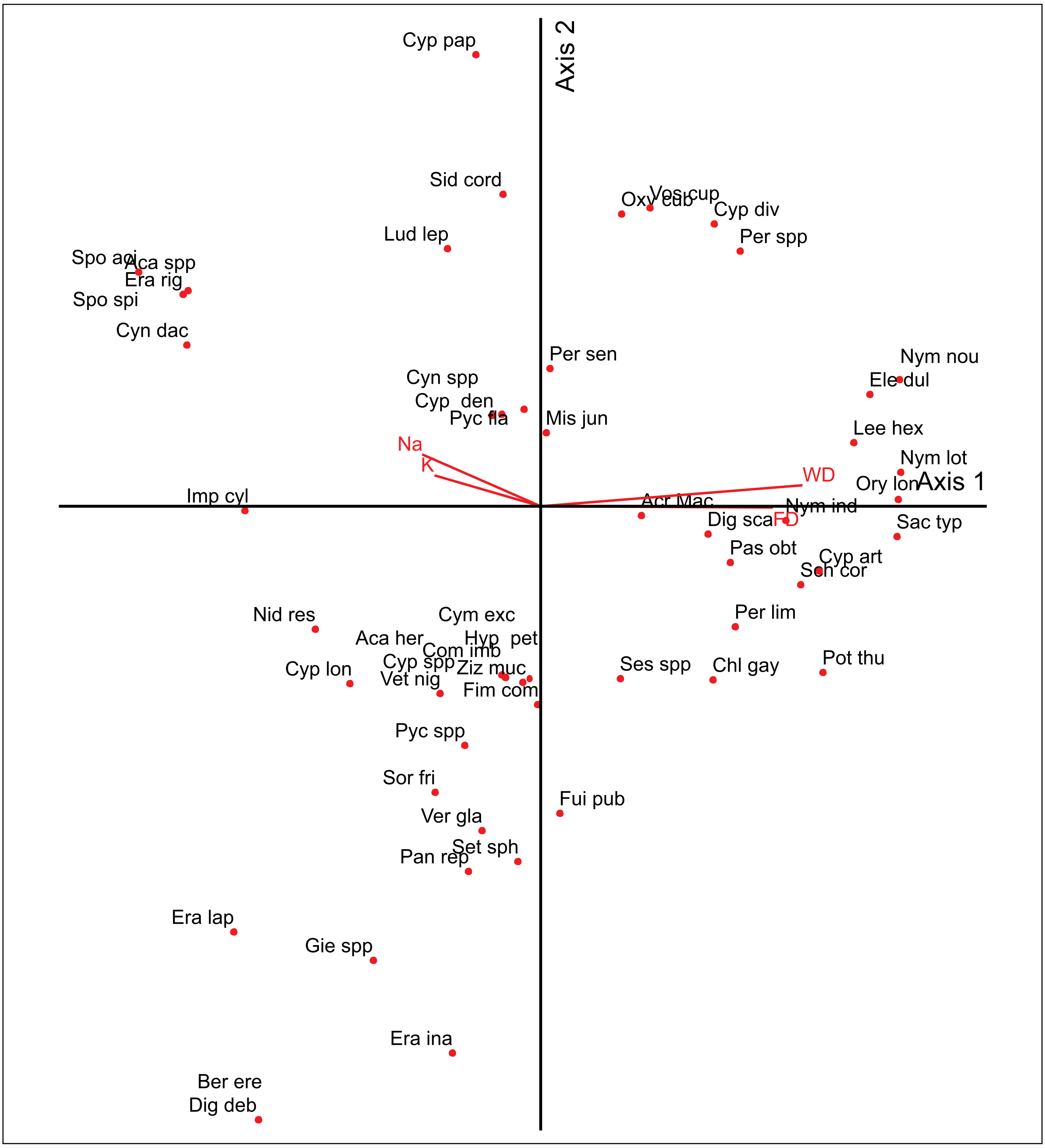

Figure 2. A biplot showing the interaction between Na, K, flooding depth (WD) and flooding duration (FD) and seasonal floodplain species before flooding.

were K, Na, Mg, pH, flooding depth and flooding duration (Figure 3).

After flooding Na, Mg, K and Ca were negatively correlated with species distributed along axes 1 and 2. Flooding duration and pH were negatively correlated to axes 1 and 2 respectively. Flooding depth was positively correlated to both axes, while P was negatively correlated to species along axis 2 (Table 5 and Figure 3).

Discussion

This study showed that there was variation in environmental factors that influence species composition and distribution of seasonal floodplain plant communities in the Okavango Delta. Factors that significantly influenced plant species composition before flooding are Na, K, water depth and flooding duration. However,

Figure 3: A biplot showing the interaction between Na, K, Mg, pH, flooding depth (WD) and flooding duration (FD) and seasonal floodplain species after flooding.

Table 4: The relationship between environmental variables and species distribution along ordination axes before flooding (N = 40)

Environmental factor	1	2
	r	r
Na	-0.474	0.314
Mg	-0.306	0.148
K	-0.448	0.239
Ca	-0.288	0.067
P	0.137	-0.154
pH	-0.357	0.210
Flooding duration (weeks)	0.660	-0.035
Flooding depth	0.701	0.039

after flooding there were additional factors of K, Mg and pH. This suggests that during flooding these cations are deposited on floodplains due to lateral water flow resulting in their increased concentration in these habitats. Another explanation of this could be evapo-concentration of K and Mg as the flood recedes, which results in increased concentrations of these elements. As a result their influence on the composition and distribution of seasonal floodplains becomes significant.

Species whose distribution was influenced by Na, Mg, K and pH include *Sporobolus spicatus*, *Sporobolus acinifolius* Stapf, *Cynodon dactylon* and *Imperata cylindrica*. These species are generally adapted to saline conditions that are associated with these chemicals. *Sporobolus* species are adapted to salinity through increased area of the root; stem, leaf blade and leaf sheath (Hameed, Ashraf & Naz 2011). Enlargement of these organs enhance the excretion of saline ions such as Na^+ and Cl^- in large quantities (Flowers & Colmer 2008). To further enhance the excretion of saline ions, *Sporobolus* species have increased vesicular hair density and developed aerenchyma tissue (Hameed, Ashraf & Naz 2011). *Cynodon dactylon* survives saline conditions through exclusion of toxic ions through leaves enhanced by increased density of vesicular hairs on both adaxial and abaxial leaf surfaces (Marcum 1999). *Imperata cylindrica* has also been found to survive saline conditions in wetland ecosystems (McDonald 2004). This plant copes with salinity through anatomical adaptations such as increased succulence of the midrib and cortical parenchyma, which may help in the sequestration of ions (Hameed, Ashraf & Naz 2009). In addition to this, Hameed, Ashraf & Naz (2009) found that *Imperata cylindrica* develops enlarged bulliform cells, which help in folding the leaves to minimise water loss during salt stress. Other anatomical adaptation strategies in *Imperata cylindrica* include reduced root area, which helps it to absorb Na^+ and Cl^- in lower quantities and development of aerenchyma tissue to enhance ion excretion (Hameed, Ashraf & Naz 2011).

Flooding duration and depth influenced species composition and distribution before flooding and after flooding. This may have implications for their survival during drought conditions caused by climate change. It is predicted that hydrological changes resulting from climate change will affect species composition and distribution such that only species that are tolerant of drought conditions survive during low water levels (Middleton 2009). The influence of flooding duration and depth is important from a management point of view in the Okavango Delta. Flooding can be manipulated from upstream impoundments of the Okavango River Basin, which will reduce the inflow into the distal regions such as the Okavango Delta in Botswana, which in turn may result in changes in floodplain species community composition and distribution. This suggests that any water abstraction from the Okavango River Basin should take into consideration the fact that flooding duration and depth are important in sustaining the species composition and distribution of seasonal floodplain plant communities such that those developments do not disturb this. However, experimental studies are still needed to give accurate predictions of seasonal floodplain plant communities to flooding duration and depth. In this study, species that were influenced by water depth include *Oryza longistaminata* A.Chev. & Roehr, *Nymphaea lotus* L., *Leersia hexandra* Sw., *Eleocharis dulcis* (Burm.f.) Trin. ex Hensch and *Nymphaea nouchali* Burm.f. These species are tolerant of prolonged flooding duration and high depth. They survive flooding conditions through development of fleshy, hollow stems and adventitious roots that grow from the submerged nodes (Ellenbroek 2012). These adaptations help in the absorption of oxygen and carbon dioxide for the processes of respiration and photosynthesis respectively. For the absorption of light they have developed large leaves to increase the surface area (Ellenbroek 2012).

The findings of this study also agree with results from studies conducted elsewhere (e.g. Gregory et al. 1991;

Table 5: The relationship between environmental variables and species distribution along ordination axes after flooding (N = 40)

Axis	1	2
	r	r
Na	-0.521	-0.139
Mg	-0.540	-0.027
K	-0.565	-0.217
Ca	-0.353	-0.237
P	0.142	-0.148
pH	-0.774	0.091
Flooding duration (weeks)	0.660	-0.314
Flooding depth	0.660	0.035

Junk 1997; Rees 1978; Zeilhofer & Schessl 1999). However, it should be noted that these studies did not investigate the intra-annual variation of environmental factors that influence the species composition and distribution in seasonal floodplain communities. In a study in the Pantanal seasonal floodplains, Zeilhofer and Schessl (1999) found that seasonal floodplain vegetation community composition and distribution were influenced by flooding depth and duration gradient. A short grassland vegetation community dominated by flood tolerant *Vochysia divergens* Pohl was found in longer-duration, deeply flooded sites, whereas a medium tall grassland vegetation community occurred in areas experiencing short flooding duration and shallow flooding depth. The influence of flooding depth and duration on seasonal floodplain plant communities was also observed in the Amazon seasonal floodplains (Gregory et al. 1991; Junk 1997; De Simone et al. 2003). The findings of Rees (1978) from a study conducted in the Kafue seasonal floodplains also agree with the observation made in this study. In that study, floodplain plant communities were distributed according to their tolerance to flooding duration and depth gradient. Regions that were frequently flooded with high flooding duration and depth were dominated by *Vossia cuspidata* (Roxb.) Griff and *Echinochloa stagnina* (Retz.) P.Beauv. In the Okavango Delta past studies also found that flooding duration and depth influence vegetation community composition and distribution (e.g. Biggs 1976; Bonyongo et al. 2000; Ellery & Tacheba 2003; Ellery et al. 1993; Murray-Hudson 2009; Smith 1976; Tsheboeng et al. 2014).

Conclusion and implications for management of floodplain plant communities in the Okavango Delta

This study has shown that there are seasonal variations in the environmental factors that influence the species composition and distribution of seasonal floodplain plant communities in the Okavango Delta. Factors that influenced plant species composition and distribution before flooding were Na, K, water depth and flooding duration. After flooding there were additional factors of K, Mg, pH. From a management perspective, this study suggests that the influence of these environmental factors should be considered before any major developments such as impoundments are implemented so that the species composition and distribution are not disturbed. To make accurate quantitative projections on the changes of species composition and distribution that may result from changes in hydrological regime, future experimental studies are needed. Those studies should quantify the quantity of water needed to sustain the seasonal floodplain plant communities in the Okavango Delta. Future studies should also investigate the changes in soil nutrient content and toxic substances associated with extended flooding duration. Such studies should also investigate the influence of flooding on primary production of seasonal plant communities.

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Competing interests

The authors declare that they have no financial or personal relationship(s) that may have inappropriately influenced them in writing this article.

Author's contributions

GT, MB & MM-H designed the study. GT & MB collected data. GT analysed data and wrote the manuscript. MM-H and MB commented on the initial drafts of the manuscript.

References

Benstead, P., Drake, M., Jose, P., Mountford, O., Newbold, C. & Treweek, J., 1997, 'The grassland guide. Managing flooding and coastal wet grasslands for wildlife', RSBP. Royal Society for the Protection of Birds, Sandy, UK.

Biggs, R.C., 1976, 'The ecology of chief's island and adjacent floodplains of the Okavango Delta', Proceedings of the symposium on the Okavango Delta and its future utilization held in Gaborone, Botswana. Gaborone, Botswana.

Bonyongo, M.C., Bredenkamp, G.J. & Veenendaal, E., 2000, 'Floodplain vegetation in the Nxaraga Lagoon area, Okavango Delta, Botswana', *South African Journal of Botany* 66, 15–21, DOI: 10.1016/S0254-6299(15)31046-2.

Cronk, J.K. & Fennessy, M.S., 2001, 'Wetland plants: biology and ecology', CRC Lewis Publishers, New York.

Davis, S.M. & Ogden, J.C., 1993, 'Everglades: The ecosystem and its restoration', St. Lucie Press, Delray Beach, Florida

De Oliveira, M.T., Damasceno-Junior, G.A., Pott, A., Filho, A.C., Suarez, Y.R. & Parolin, P., 2014, 'Regeneration of riparian forests of the Brazilian Pantanal under flood and fire influence,' *Forest Ecology and Management* 331, 256–263, DOI: 10.1016/j.foreco.2014.08.011.

De Simone, O., Junk, W.J. & Schmidt, W., 2003, 'Central Amazon Floodplain Forest: root adaptations to flooding', *Russian Journal of Plant Physiology* 50, 848–855, https://doi.org/10.1023/B:RUPP.0000003285.70058.4c.

Edwards, P.J. & Kollman, J., 2002, 'Life history of evolution in Lodoicea maldivica (Arecaceae),' *Nordic Journal of Botany* 22, 227–238, https://doi.org/10.1111/j.1756-1051.2002.tb01371.x.

Ellenbroek, G.A., 2012, 'Ecology and productivity of an African wetland system: the Kafue Flats, Zambia', Dr W. Junk Publishers, Dordrecht.

Ellery, K., Ellery, W.N., Rogers, K.H. et al., 1991, 'Water depth and biotic insulation: Major determinants of back-swamp plant community composition', *Wetlands Ecology and Management* 1, 149–162, https://doi.org/10.1007/BF00177289.

Ellery, W.N. & Tacheba, B., 2003, 'Floristic Diversity of the Okavango Delta, Botswana', In: Alonso, L.E. & Nordin, L.A (eds), 'A rapid biological assessment of the aquatic ecosystems of the Okavango Delta, Botswana: High water survey', RAP-Bulletin of Biological Assessment 25, 69–96.

Ellery, W.N., Ellery, K. & McCarthy, T.S., 1993, 'Plant distribution in islands of the Okavango Delta, Botswana: determinants and feedback interactions', *African Journal of Ecology* 31, 118–134, https://doi.org/10.1111/j.1365-2028.1993.tb00526.x.

Flowers T.J. & Colmer, T.D., 2008, 'Salinity tolerance in halophytes', *New Phytologist* 179, 945–963, https://doi.org/10.1111/j.1469-8137.2008.02531.x.

Gregory, S.V., Swanson, F.J., Mckee, W.A. & Cummins, K.W., 1991, 'Ecosystem perspective of riparian zones', *Bioscience* 41, 540–551, DOI: 10.2307/1311607.

Growing, D.J.G., Spoor, G. & Mountford, O. 1998, 'The influence of minor variations in hydrological regime on grassland plant communities: implications for water management', In: 'Joyce, C.B & Wade, P.M (eds), European wet grasslands: biodiversity, management and restoration', Wiley, Chichester, 217–227.

Gumbricht, T., McCarthy, J. & McCarthy, T.S., 2004, 'Channels, wetlands and islands in the Okavango Delta, Botswana, and their relation to hydrological and sedimentological processes', *Earth Surf. Process Landforms* 29, 15–29, DOI: 10.1002/esp.1008.

Hameed, M., Ashraf, M. & Naz, N. 2009, 'Anatomical adaptations to salinity in cogon grass (Imperata cylindrical (L.) Raeuschel) from the Salt Range, Pakistan', *Plant and Soil* 322: 229–238, DOI: 10.1007/s11104-009-9911-6.

Hameed, M., Ashraf, M. & Naz, N., 2011, 'Anatomical and physiological characteristics relating to ionic relations in some salt tolerant grasses from the Salt Range, Pakistan', *Acta Physiologiae Plantarum*', 33, 1399–1409, DOI: 10.1007/s11738-010-0674-8.

Junk, W.J., 1997, 'General aspects of floodplain ecology with special reference to Amazonian floodplains', In Junk, W.J (ed), 'The central Amazon floodplain: Ecology of a pulsing system – Ecological Studies', 126, 3–20.

Kozlowski, T.T., 1984, 'Plant responses to flooding of soil', *Bioscience* 34,162–167.

Kruskal, J.B., 1964, 'Nonmetric multidimensional scaling: a numerical method', *Psychometrika* 29, 115–129, https://doi.org/10.1007/BF02289694.

MacDonald, G.E., 2004, 'Cogongrass (Imperata cylindrica) – biology, ecology, and management', *Critical Reviews in Plant Sciences* 23, 367–380, https://doi.org/10.1080/07352680490505114.

Marcum, K.B., 1999, 'Salinity tolerance mechanisms of grasses in the subfamily Chloridoideae', *Crop Science* 39, 1153–1160, https://doi.org/10.2135/cropsci1999.0011183X003900040034x.

Mather, P.M., 1976, 'Computational methods of multivariate analysis in physical geography', John Wiley and Sons, London.

McCarthy, T.S. & Ellery, W.N., 1998, 'The Okavango Delta', *Transactions of the Royal Society of South Africa* 53, 157–182, https://doi.org/10.1080/00359199809520384.

McCarthy, T.S., 2006, 'Groundwater in the wetlands of the Okavango Delta, Botswana, and its contribution to the structure and function of the ecosystem', *Journal of Hydrology*, 320, 264–282, https://doi.org/10.1016/j.jhydrol.2005.07.045.

McCune, B. & Grace, J.B., 2000, 'Analysis of ecological communities', MjM software, Gleneden Beach, Oregon, U.S.A.

Merritt, D.M., Scott, M.L., Poff, N.L., Auble, G.T. & Lytle, D.A., 2009, 'Theory, methods and tools for determining environmental flows for riparian vegetation: riparian vegetation-flow response guilds', *Freshwater Biology*, 55, 206–225, doi:10.1111/j.1365-2427.2009.02206.x.

Middleton, B.A., 2009, 'Vegetation status of the Keoladeo National Park, Bharatpur, Rajasthan, India', US Geological Survey, Report 2009-5193.

Mueller-Dombois, D. & Ellenberg, H., 1974, 'Aims and methods of vegetation ecology', John Wiley & Sons, New York.

Murray-Hudson, M. 2009, 'Floodplain vegetation responses to flood regime in the seasonal Okavango Delta, Botswana', PhD thesis, University of Florida, Florida.

Naiman, R.J. & Decamps, H., 1997, 'The ecology of interfaces: Riparian zones', *Annual Review of Ecology and Systematics* 28, 621–658, https://doi.org/10.1146/annurev.ecolsys.28.1.621.

Oliveira-Filho, A.T., Vilela, E.A., Gavilanes, M.L. & Carvalho, D.A., 1994, 'Effects of flooding regime on understorey bamboos on the physiognomy and tree species composition of a tropical semi-deciduous forest in southern Brazil', *Vegetation* 113, 99–124, https://doi.org/10.1007/BF00044229.

Parolin, P., Ambrüster, N. & Junk, W.J., 2006, 'Two Amazonia trees react differently to periodical flooding', *Tropical Ecology* 47, 243–250.

Pinder, L. & Rosso, S., 1998, 'Classification and ordination of plant formations in the Pantanal of Brazil', *Plant Ecology* 136, 151–165, https://doi.org/10.1023/A:1009796616824.

Ponce, V.M. & Da Cunha, C.N., 1993, 'Vegetated earth mounds in tropical savannas of central Brazil: A synthesis', *Journal of Biogeography*, 20, 219–225.

Rees, W.A., 1978, 'The Ecology of Kafue Lechwe: soils, water levels and vegetation', *Journal of Applied Ecology* 15, 163–176, DOI: 10.2307/2402928.

Smith, P., 1976, 'An outline of the vegetation of the Okavango Drainage system', Proceedings of the symposium on the Okavango Delta and its future utilization, National museum, Gaborone, Botswana.

Toogood, S.E., Joyce, S. & Waite, S., 2008, 'Response of floodplain grassland communities to altered water regimes', *Plant Ecology* 197, 285–298, DOI: 10.1007/s11258-007-9378-6.

Tsheboeng, G., Bonyongo, M. & Murray-Hudson, M., 2014, 'Flood variation and soil nutrient content in floodplain vegetation communities in the Okavango Delta', *South African Journal of Science* 110, 1–5.

Wilson, B.H. & Dincer, T., 1976, 'An introduction to the hydrology and hydrography of the Okavango Delta', Proceedings of the Symposium on the Okavango Delta and its future utilization, National Museum, Gaborone, Botswana.

Wolski, P., Savenije, H.H.G., Murray-Hudson, M. & Gumbricht, M., 2006, 'Modelling of the flooding in the Okavango Delta, Botswana, using a GIS model', *Journal of Hydrology* 331, 58–72, DOI: 10.1016/j.jhydrol.2006.04.040.

Zeilhofer, P. & Schessl, M., 2000, 'Relationship between vegetation and environmental conditions in the Northern Pantanal of Mato Grosso, Brazil', *Journal of Biogeography* 27, 159–168, https://doi.org/10.1046/j.1365-2699.2000.00357.x.

Supplementary Information

Supplementary Table 1: Full plant species names for Figures 2 and 3. *Please note that some of these names are no longer considered to be current (e.g. *Acacia erioloba*), however, since these are the names that were entered into the software used for the analyses, they are provided here for reference purposes.

Abbreviation	Full name
Aca eri	*Acacia erioloba*
Aca heb	*Acacia hebeclada*
Acr mac	*Acroceras macrum*
Ber ere	*Berula erecta*
Chl gay	*Chloris gayana*
Com imb	*Combretum imberbe*
Cyc tub	*Cycnium tubulosum*
Cym exc	*Cymbopogon excavatus*
Cyn dac	*Cynodon dactylon*
Cyp art	*Cyperus articulatus*
Cyp den	*Cyperus denudatus*
Cyp div	*Cyperus dives*
Cyp lon	*Cyperus longus*
Cyp pap	*Cyperus papyrus*
Dig deb	*Digitaria debilis*
Dig sca	*Digitaria scalarum*
Ele dul	*Eleocharis dulcis*
Era ina	*Eragrostis inamoena*
Era lap	*Eragrostisl appula*
Era rig	*Eragrostis rigidior*
Fim com	*Fimbristylis complanata*
Fui pub	*Fuirena pubescens*
Gis afr	*Gisekia africana*
Gom fru	*Gomphocarpus fruticosus*
Hyp pef	*Hyphaene petersiana*
Imp cyl	*Imperata cylindrica*
Lee hex	*Leersia hexandra*

Abbreviation	Full name
Lud lep	*Ludwigia stolonifera*
Mis jun	*Miscanthus junceus*
Nid res	*Niderolla resedifolia*
Nym ind	*Nymphoides indica*
Nym lot	*Nymphoides lotus*
Nymnou	*Nymphoides nouchali*
Ory lon	*Oryza longistaminata*
Oxy cub	*Oxycaryum cubense*
Pan rep	*Panicum repens*
Pas obt	*Paspalidium obtusifolium*
Pec-loe	*Pechuel-loeschea leubnitziae*
Per lim	*Persicaria limbata*
Per sen	*Persicaria senegalensis*
Pot thu	*Potamogetum thunbergii*
Pyc fla	*Pycreus flavescens*
Sac typ	*Sacciolepis typhura*
Sch cor	*Schoenoplectus corymbosus*
Set sph	*Setaria sphacelata*
Sid cord	*Sida cordifolia*
Sor fri	*Sorghastrum friesii*
Sph fri	*Sphaeranthus friesii*
Spo aci	*Sporobolus acinifolius*
Spo spi	*Sporobolus spicatus*
Ver gla	*Vernonia glabra*
Vet nig	*Vetiveria nigritana*
Vos cusp	*Vossia cuspidata*
Ziz muc	*Ziziphus mucronata*

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Checklist of the pimeliine darkling beetles of the Vhembe Biosphere Reserve, South Africa (Coleoptera: Tenebrionidae: Pimeliinae)

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Abstract: A checklist of genera and species of the Pimeliinae (Tenebrionidae: Coleoptera) of the Vhembe Biosphere Reserve is provided. A total of 36 species are recorded. We provide brief biological notes on the tribes recorded from the Vhembe Region.

Keywords: Darkling beetles, biological notes, Savanna Biome, Limpopo Province, Soutpansberg

Introduction

Of the ground-living beetles, Tenebrionidae Latreille 1802 (darkling beetles) rank as the seventh most speciose group of beetles (Kergoat et al. 2014). They are important detritivores and granivores, and constitute a significant food source for reptiles and small mammals, especially in arid and semi-arid environments (Polis et al. 1998).

The darkling beetles of Africa are poorly known, with few taxonomists available to describe new species, revise groups and offer assistance in determination of specimens. Yet these beetles show possibly higher levels of diversity in the southern hemisphere than in the northern hemisphere, and latitudinal gradients in diversity do not quite follow trends observed north of the equator (Platnick 1991). The Cape Floristic Region is abundant in tenebrionid tribes that have few or no representatives in the sub-tropical savannah (Botes, McGeoch & Chown 2007; Endrödy-Younga 1988; Kamiński 2016), inadvertently giving the impression that this family is species poor in the rest of South Africa (Gerlach, Samways & Pryke 2013).

The Tenebrionidae are remarkably diverse in the arid and semi-arid western regions of southern Africa (Koch 1962a) including the Northern Cape, Namibia and southern Angola; some groups, such as *Caenocrypticus*, are restricted to this region (Endrödy-Younga 1996). Nevertheless, arid associated taxa (Koch 1962a) are encountered in the northern bushveld, especially the Limpopo Valley north of the Soutpansberg. At least 40 tribes are known to occur in sub-Saharan Africa (Heyns 1959). Many of the southern African Pimellinae were reviewed earlier by Koch (1955) as part of his delineation of the subfamily 'Tentyriinae', according to which the abdomen has an intersegmental membrane between the distal segments, a still useful morphological feature in separating members of the subfamily from others. The largest tribe in South Africa is the Sepidiini Eschscholtz, 1829, or *toktokkies*, which can be distinguished from other tribes by the presence of a trochantin on the meso-coxae. Koch (1955) provides a key to the tribes.

This checklist covers only the pimeliine darkling beetle fauna of the Vhembe Biosphere Reserve, which is known to have rich plant (Hahn 1994) and spider (Foord, Dippenaar-Schoeman & Van der Merwe 2002) diversity, but with significant gaps in our knowledge of other hyper-diverse taxa in the region. The classification is that of Bouchard et al. (2005).

Methods and Materials

Twenty sites in the VBR Vhembe Biosphere Reserve (VBR), situated in Limpopo Province, South Africa were sampled using pitfall traps (maps were drawn using vector layers from DIVA-GIS) (Figure 1). These sites were located in the following vegetation units (Mucina & Rutherford 2006): Makhado Sweet Bushveld (3 sites), Soutpansberg Summit Sourveld (4 sites), Northern Mistbelt Forest (4 sites), Roodeberg Bushveld (2 sites), Soutpansberg Mountain Bushveld (4 sites), Musina Mopane Bushveld (2 sites), and Limpopo Ridge Bushveld (1 site) (Figure 2). Pitfall traps (7 cm diameter, 12 cm deep) were dug into the ground and a quarter filled with propylene glycol. Left out for seven days, as was done here, it is possible to attain inventory completion for each point. After collection, the contents of each trap were washed using a fine net, and stored in 96% ethanol. Thereafter, the specimens from each trap were sorted into pill vials with acquisition numbers placed in each.

Darkling beetles were then sorted to morphospecies and where possible identified to the tribe level using Koch (1955). Tenebrionidae identifications were then confirmed to genus and species level by Ruth Müller (Ditsong National Museum of Natural History), and Mary Louise Penrith (retired entomologist). Vouchers of each species are housed in the Coleoptera Collection of the Ditsong Museum of Natural History and in the UNIVEN Natural History Collection.

In this paper we present photos, depicting 26 species of Tenebrionidae found in the VBR (Figure 3), and representing 16 genera. The photos were taken with a Canon 450D camera with a F2.8 100 mm lens by Dawn Cory Toussaint, who also edited the images to remove shadows and increase clarity and contrast.

This checklist of the pimeliine darkling beetles of the VBR is the first published record of a major ground-dwelling beetle family for the region. Infraspecific taxa are not distinguished in the checklist presented here. We include suspected species (designated with cf.) and morphospecies (identified to genus and tribe) in the checklist, highlighting future taxonomic research needs.

Results and Biological Notes

A total of 36 Pimeliine darkling beetles were sampled distributed in seven tribes. Provided is a quick overview of each tribe occurring in the VBR.

The Adesmiini are pear-shaped beetles with slender, spindly mid- and hind-legs, often longer than the anterior legs, and distinctive elytral sculpturation. They are sun-loving, flightless, fast running beetles that occupy the savannah, grassland and desert biome. Their centre of diversity is Namibia and Botswana. Adesmiini were treated by Koch (1951), and Penrith (1979a, 1986) who provides keys to the genera and species. Three species were sampled in the VBR.

Most sub-Saharan genera of Asidini are endemic to southern Africa and Madagascar (Koch 1962b). The head is partly hidden from above, the pronotum has prominent lobes located antero-laterally, while the elytra are strongly convex with ridges and tubercles present, sometimes with a pair of sharply elevated costae.

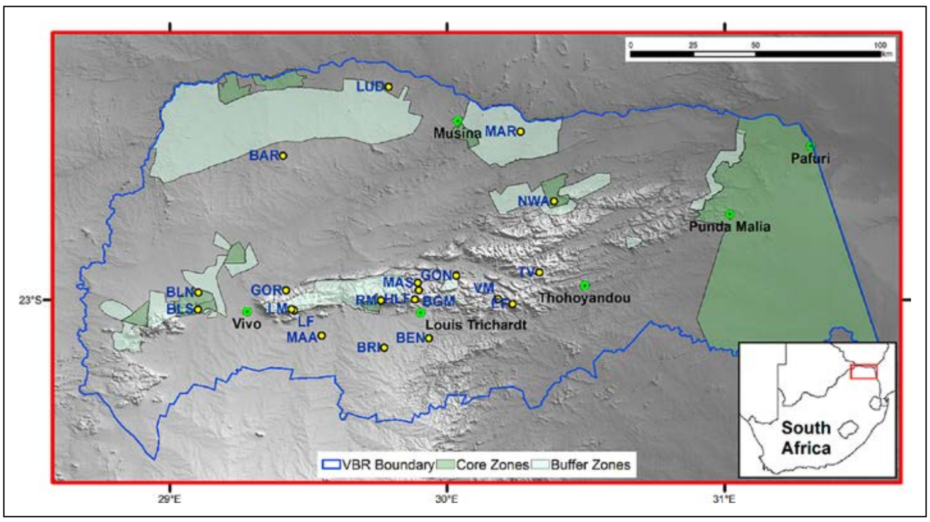

Figure 1. Map of the Vhembe Biosphere Reserve showing distribution of existing core and buffer zones and transition areas; current core areas in dark green and buffer zones in lighter green, and outline of the reserve in blue. The remainder of the area outlines in blue is transition area.

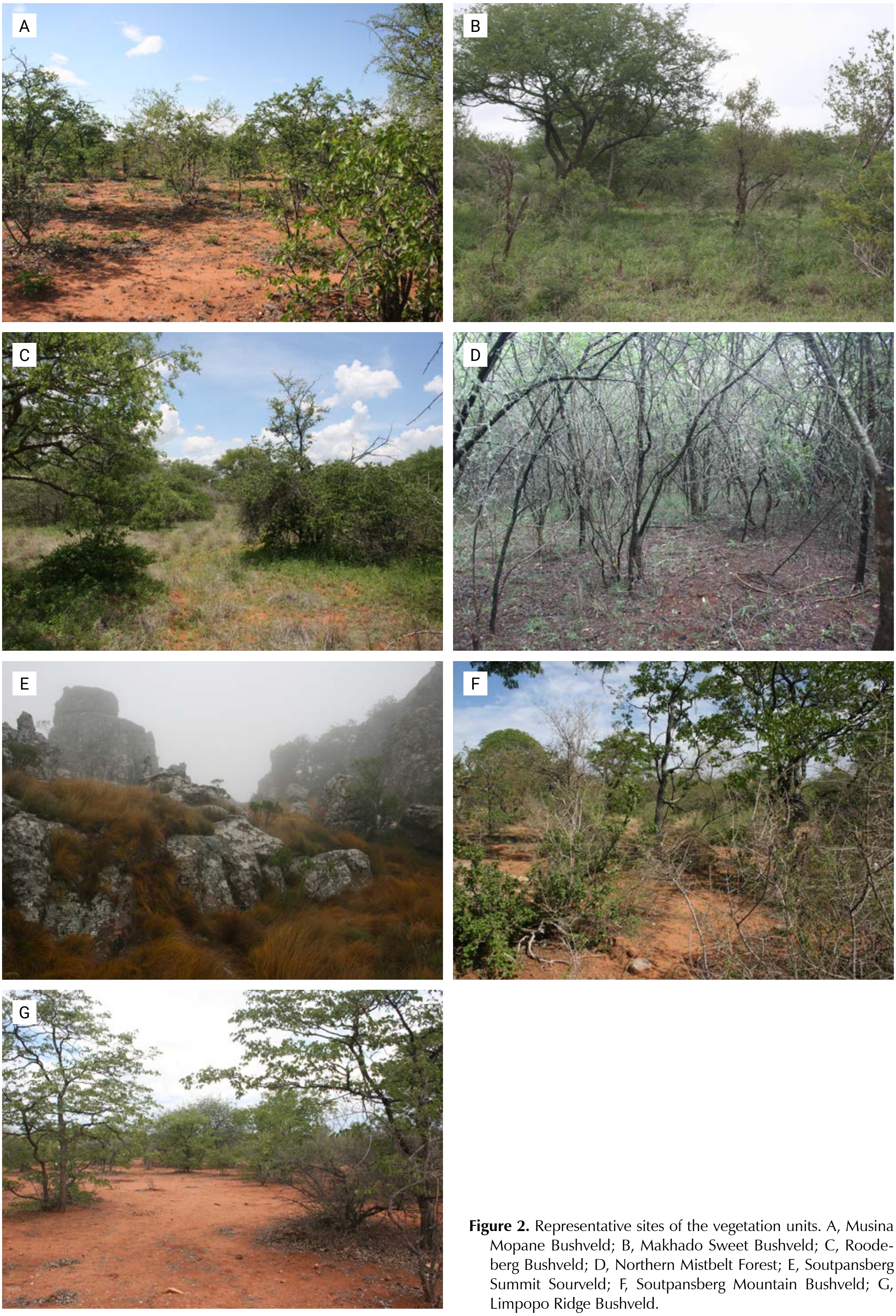

Figure 2. Representative sites of the vegetation units. A, Musina Mopane Bushveld; B, Makhado Sweet Bushveld; C, Roodeberg Bushveld; D, Northern Mistbelt Forest; E, Soutpansberg Summit Sourveld; F, Soutpansberg Mountain Bushveld; G, Limpopo Ridge Bushveld.

Figure 3. A, *Renatiella reticulata*; B, *Amachla schmidti*; C, *Amachla sulcicollis*; D, *Amachla echinoderma*; E, *Amachla* sp. A; F, *Machlomorpha* cf. *evanida*; G, *Machlomorpha* cf. *mossambica*; H, *Himatismus* sp. A; I, *Eurychora barbarta*; J, *Eurychora* sp. A; K, *Pogonobasis ovatus*; L, *Serrichora fahraei*; M, *Amiantus* cf. *gibbosus*; A–M, scale = 1 cm

Figure 3 (continued). N, *Amiantus pusillus*; O. *Dichtha cubica*; P, *Moluris discoidea*; Q, *Psammodes rowleianus*; R, *Ocnodes (Ocnodes) scrobicolle*; S, *Psammodes* cf. *janitor*; T, *Psammodes* cf. *ventricosus*; U, *Psammophanes* sp. A; V, *Somaticus (Trichotrichus) angulatus*; W, *Somaticus (Trichotrichus) varicollis*; X, *Somaticus (Somaticus) aeneus*; Y, *Ossiporis terrena fragilis*; Z, *Zophosis (Oculosis)* sp. A.; N–Z, scale = 1 cm.

Koch (1962b) revised the sub-Saharan genera, of which there are seven: *Amachla*, *Machla*, *Asidomorpha*, *Machlomorpha*, *Machleida*, *Afrasida* and *Cryptasida*. They are found predominantly in montane habitat and afromontane forest in undergrowth and may be hard to collect (Koch 1955). A total of six species are recorded.

The Adelostomini, referred to by Koch (1955) and Scholtz and Holm (1985) as Eurychorini Solier, 1837, are specialised tenebrionids with approximately 20 endemic South African genera (Koch 1955). The vertex of the head is slightly concave in dorsal view, with a narrow neck, the pronotum has broad lateral flanges. The elytra are also very broad. Several genera have stridulatory organs on the inner surface of the middle femora (Schawaller 2007). They often bear soil particles and other debris held by long hairs on the dorsal surface, which may be indicative of myrmecophyly (Schawaller 2007). Koch (1952) provides keys to the different genera. Brown (1958) summarises information on the distribution of the genera in South Africa. Genera recorded from the VBR are *Eurychora*, *Pogonobasis* and *Serrichora*. Other genera that may occur in the Vhembe region (not sampled for this study) include *Geophanus*, *Prunaspila* and *Phytolostoma*.

The Sepidiini, refered to by Koch (1955) and Scholtz and Holm (1985) as Molurini Solier, 1834 are flightless beetles, usually strongly convex and globular; the elytra are extremely variable in shape, and loosely attached to the pronotum. The presence of a membrane between the distal sternal segments, of a trochantin on the mesocoxae, and a very broad scutellum above the elytra serve to differentiate the Sepidiini, or *toktokkies*, from other Tenebrionidae. Sepidiini generally show a smooth, punctate or costate type of elytral sculpturation in which raised longitudinal costal elements dominate the sculpture patterns – these may be smooth, denticulate or irregular (Koch 1955). Their common name derives from the habit of rapidly tapping the ground with the abdomen to attract a mate. About 1000 species and many genera occur over the African continent. The Sepidiini are a mostly sub-Saharan group, but with representatives in the Sahara and the Middle-East. Koch (1955) provides a key to subtribes. Kamiński et al. (2019) has produced a catalogue of the world fauna of this tribe. This was by far the most diverse tribe with 16 species sampled.

Zophosini or coffee-bean beetles are often seen running very rapidly over bare ground (Picker, Griffiths & Weaving 2004). When caught they are usually covered with a fine yellow dust, which rubs off when handled. The tribe is monogeneric, but there are many sub-genera and species and they are often the most abundant beetles in pitfalls (Penrith 1977). The elytra may display small pits, raised costae, or be completely smooth. Their centre of diversity is the arid western part of southern Africa, including Angola (Koch 1958). Penrith (1977, 1979b–1983) revised the tribe.

The tribe Cryptochilini is very poorly represented in the VBR, as their centre of diversity is the arid southwest of Africa, occurring especially in the Northern Cape, Namibia and Angola. Penrith & Endrödy-Younga (1994) revised the tribe.

Discussion

Subsets of the Tenebrionidae community of the VBR show strong regional associations, influenced not just by environmental variables, but by biogeography, such as the psammophylous Sepidiini associated with the mega-Kalahari deep-sands (Koch 1962a), and Platynotina radiations associated with the Bushveld Igneous complex (Endrödy-Younga 1988, Kamiński & Iwan 2013). Otherwise summer-rainfall faunas dominate the taxonomic composition, even at tribal level, with distributions extending into the tropics: a trend observed in other families as well (Davis, Frolov & Scholtz 2008).

There is a need to generate data on species turnover affected by broad scale environmental variables (Hawkins et al. 2003), beetle biogeography and zoogeographic provinces in the light of new data (Holm et al. 1984; Wharton & Robert, 1982). Furthermore, very little has been done on studying the ecosystem services provided by Tenebrionidae and Carabidae, especially in arid ecosystems where these taxa are particularly prominent.

The major purpose of this study is to highlight the necessity of continuing to sample and compare faunal assemblages between major biogeographic regions or biomes, focusing on poorly sampled regions. The South African National Survey of Arachnida (Dippenaar-Schoeman et al. 2015) provides a tried and tested protocol that can be emulated to catalogue and promote the beetle diversity of South Africa, generating biodiversity data that can provide valuable information to the scientific community.

Checklist

TENEBRIONIDAE *Latreille, 1802*

PIMELIINAE *Latreille, 1802*

Adesmiini Lacordaire, 1859

Cephaladesmia arachnoides *Gerstaecker* (?) LUD
Renatiella reticulata *(Gerstaeker, 1854)* Fig. 3A, MAR, BAR, BLN, GON, LUD, NWA
Stenocara aenescens *Haag, 1875* LUD

Table 1. Index of geographical names and abbreviations used in the checklist

Abbreviation	Site	Vegetation type	Latitude	Longitude
BAR	Barries Farm	Musina Mopane Bushveld	-22.48	29.41
BEN	Ben Lavin Nature Reserve	Makhado Sweet Bushveld	-23.13	29.92
BGM	Bluegumspoort (Farm)	Soutpansberg Summit Sourveld	-22.96	29.89
BLN	Blouberg NR North	Roodeberg Bushveld	-22.98	29.12
BLS	Blouberg NR South	Roodeberg Bushveld	-23.02	29.09
BRI	Bristow Farm	Makhado Sweet Bushveld	-23.17	29.76
EF	Entabeni State Forest	Northern Mistbelt Forest	-23.01	30.24
GON	Gondeni (Communal land)	Soutpansberg Mountain Bushveld	-22.91	30.06
GOR	Goro Game Reserve	Soutpansberg Mountain Bushveld	-22.93	29.42
HLF	Hanglip State Forest	Northern Mistbelt Forest	-22.99	29.88
LF	Lajuma Forest	Northern Mistbelt Forest	-23.03	29.44
LM	Lajuma Mistbelt	Soutpansberg Summit Sourveld	-23.02	29.43
LUD	Ludwig's Lust Farm	Limpopo Ridge Bushveld	-22.25	29.78
MAA	Mara Research Station	Makhado Sweet Bushveld	-23.14	29.55
MAR	Maremani Game Reserve	Limpopo Ridge Bushveld	-22.39	30.23
MAS	Mashovela Lodge	Soutpansberg Mountain Bushveld	-22.93	29.89
NWA	Nwanedi Game Reserve	Soutpansberg Mountain Bushveld	-22.64	30.37
RM	Happy Rest	Soutpansberg Summit Sourveld	-23.01	29.75
TV	Thatevondo State Forest	Northern Mistbelt Forest	-22.91	30.33
VM	Vhuvha (Communal land)	Soutpansberg Summit Sourveld	-22.99	30.18

Asidini Fleming, 1821

Amachla schmidti *Wilke*, 1924 Fig. 3B, BEN, BLS, MAS
Amachla sulcicollis *(Fåhraeus, 1870)* Fig. 3C, MAR, BLS, MAA
Amachla echinoderma *Fairmaire, 1899* Fig 3D, VM, LM
Amachla sp. A, Fig. 3E. BLS
Machlomorpha cf. evanida *Wilke, 1924* Fig. 3F, BEN, LM, VM
Machlomorpha cf. mossambica *Péringuey*, Fig. 3G, 1899 EF, VM

Epitragini

Himatismus sp. A, Fig. 3H, BRI, LM, LUD

Adelostomini Solier, 1834

Eurychora barbarta *Olivier, 1795* Fig. 3I, MAR, BRI
Eurychora sp. A, Fig. 3J, RM, GON
Pogonobasis ovatus *Fåhraeus, 1870* Fig. 3K, GOR, LM, LF
Serrichora fahraei *(Haag 1872)* Fig. 3L, GON, LM, RM

Sepidiini Eschscholtz, 1829

Amiantus cf. gibbosus *Fåhraeus, 1870* Fig. 3M, BLN, BRI
Amiantus pusillus *Péringuey, 1904* Fig. 3N, BLS, BRI
Dichtha cubica *(Guérin-Méneville, 1845)* Fig. 3O, BEN, BGM, BRI, GON, GOR, MAS, NWA
Moluris discoidea *(Guérin-Méneville, 1845)* Fig. 3P, BAR, BEN, BLN, BLS, BRI, GON, GOR, MAA
Euphrynus carinatus *(Fåhraeus, 1870)* BLN
Psammodes rowleianus *(Westwood, 1864)* Fig. 3Q, BRI
Ocnodes (Ocnodes) scrobicolle *(Fåhraeus, 1870)* Fig. 3R, BGM, BLN, BLS, BRI, GON, GOR, LUD, MAS, NWA
Psammodes cf. janitor *Koch, 1953* Fig. 3S, BRI, MAA
Psammodes cf. ventricosus *Fåhraeus, 1870* Fig. 3T, MAS
Psammodes vialis *(Burcell, 1822)* BLN, GON, GOR
Psammophanes sp. A Fig. 3U, RM, LM
Somaticus cf. (Trichotrichus) metropolis *Koch, 1955* RM
Somaticus (Trichotrichus) angulatus *(Fåhraeus, 1870)* Fig. 3V, MAS
Somaticus (Trichotrichus) varicollis *Koch, 1955* Fig. 3W, RM
Somaticus (Somaticus) aeneus *(Solier, 1843)* Fig. 3X, TV
Ossiporis terrena fragilis *(Fåhraeus, 1870)* Fig. 3Y, BLS

Zophosini Solier, 1834

Zophosis (Zophosis) sp. A *Deyrolle, 1867* BAR, BLS
Zophosis (Hologenosis) sp. A *Fåhraeus, 1870* LUD, MAR, BLS

Zophosis (Oculosis) sp. A *Solier, 1834* Fig. 3Z, BAR, BLN
Zophosis (Oculosis) sp. B *Gerstaecker, 1854* BAR
Zophosis (Oculosis) sp. C *Penrith, 1983* BAR, BEN

Cryptochilini Solier, 1840

Cychrochile pluricostata *Penrith, 1994* LM

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References

Botes, A., McGeoch, M.A. & Chown, S.L., 2007, 'Ground-dwelling beetle assemblages in the northern Cape Floristic Region: Patterns, correlates and implications', *Austral Ecology* 32(2): 210–224, https://doi.org/10.1111/j.1442-9993.2007.01681.x

Bouchard, P. Lawrence, J.F., Davies, A.E. & Newton, A.F., 2005, 'Synoptic classification of the world Tenebrionidae (Insecta: Coleoptera) with a review of family-group names', *Annales Zoologici* 55(4): 499–530.

Brown, H.D., 1958, 'A new species of *Stipsostoma* Koch (Col., Tenebrionidae), with a key to the species and distribution map of the tribe Eurychorini in Southern Africa', *Journal of the Entomological Society of Southern Africa* 21(2): 415–422.

Davis, A.L.V., Frolov, A.V. & Scholtz, C.H., 2008, *The African dung beetle genera,* Protea Book House, Pretoria.

Dippenaar-Schoeman, A.S., Haddad, C.R., Foord, S.H., Lyle, R., Lotz, L.N. & Marais, P., 2015, South African national survey of Arachnida (SANSA): review of current knowledge, constraints and future needs for documenting spider diversity (Arachnida: Araneae). *Transactions of the Royal Society of South Africa* 70(3): 245–275, DOI: 10.1080/0035919X.2015.1088486.

Endrödy-Younga, S., 1988, 'Revision of the Genus *Anomalipus* Latreille, 1846 (Coleoptera: Tenebrionidae: Platynotini)', *Transvaal Museum Monographs* 6: 1–129.

Endrody-Younga, S., 1996, 'Revision of the tribe Caenocrypticini: (Coleoptera: Tenebrionidae: Tentyriinae). Taxonomy Tribe Caenocrypticini Genus Caenocrypticus and subgenera' *Transvaal Museum Monographs* 11(1).

Foord, S.H., Dippenaar-Schoeman, A.S. & Van der Merwe, M, 2002, 'A checklist of the spider fauna of the Western Soutpansberg, South Africa (Arachnida: Araneae)', *Koedoe* 45(2): 35–43, DOI: 10.4102/koedoe.v45i2.25.

Gerlach, J., Samways, M.J. & Pryke, J., 2013, 'Terrestrial invertebrates as bioindicators: an overview of available taxonomic groups', *Journal of Insect Conservation* 17: 831–850, DOI: 10.1007/s10841-013-9565-9.

Hahn, N., 1994, *Tree list of the Soutpansberg,* Pretoria: Fantique Publishers.

Hawkins, B.A., Field, R., Cornell, H.V., Currie, D.J., Guégan, J.F., Kaufman, D.M., Kerr, J.T., Mittelbach, G.G., Oberdorff, T., O'Brien, E.M. & Porter, E.E., 2003, 'Energy, water, and broad-scale geographic patterns of species richness', *Ecology* 84(12): 3105–3117.

Heyns, J., 1959, *The secondary sexual characters of some southern African Tenebrionidae*, Unpublished PhD thesis, University of Pretoria.

Holm, E., Scholtz, C.H., Louw, S. & Penrith, M.L., 1984 'Notes on the coleopterous fauna of the Kalahari', *Koedoe* 27(2): 153–165.

Kamiński, M.J., 2016, 'Catalogue and distribution of the subtribe Eurynotina (Coleoptera: Tenebrionidae: Pedinini)', *Annales Zoologici* 66(2): 227–266, DOI: 10.3161/00034541ANZ2016.66.2.006.

Kamiński, M.J. & Iwan, D., 2013, 'Taxonomy, distribution and ecological niche models of the Afrotropical platynotoid Platynotina (Tenebrionidae: Pedinini)', *Annales Zoologici* 63(4): 653–733, DOI: 10.3161/000345413X676795.

Kamiński, M.J., Kanda, K., Lumen, R., Ulmer, J.M., Wirth, C.C., Bouchard, P., Aalbu, R., Mal, N. & Smith, A.D., 2019, 'A catalogue of the tribe Sepidiini Eschscholtz, 1829 (Tenebrionidae, Pimeliinae) of the world', *ZooKeys* 844: 1–121, DOI: 10.3897/zookeys.844.34241. eCollection 2019.

Kergoat, G.J., Soldati, L., Clamens, A.L., Jourdan, H., Jabour-Zahab, R.O.U.L.A., Genson, G., Bouchard, P. & Condamine, F.L., 2014, 'Higher level molecular phylogeny of darkling beetles (Coleoptera: Tenebrionidae)', *Systematic Entomology* 39(3): 486–499, https://doi.org/10.1111/syen.12065.

Koch, C., 1950, 'The Tenebrionidae of southern Africa. I. First account of the Tenebrionidae collected on the University of California – Transvaal Museum Expedition, 1948', *Annals of the Transvaal Museum* 21: 273–367.

Koch, C., 1951, 'The Tenebrionidae of southern Africa. VII. Preliminary notes on the South African Adesmiini', *Annals of the Transvaal Museum* 21, 385–417.

Koch, C., 1952, 'The Tenebrionidae of Southern Africa, 7. Materials for a Monographic study on Eurychorini. Coleoptera', *Bulletin de la Société Royale Fouaud 1er d'Entomologie* 36(1): 1–125.

Koch, C., 1953, 'The Tenebrionidae of southern Africa. XXI. On some new endemic Opatrinae from the Namib Desert', *Annals of the Transvaal Museum* 22: 231–252.

Koch, C., 1954, 'The Tenebrionidae of southern Africa. XXV. New, forgotten or Palaearctic genera and species of Opatrinae', *Annals of the Transvaal Museum* 22: 419–476.
Koch, C., 1955, 'Monograph of the Tenebrionidae of southern Africa, Tentyriinae, Molurini I', *Memoirs of the Transvaal Museum* 1: 1–292.
Koch, C., 1958, 'Tenebrionidae of Angola', *Publicaçoes Culturais da Companhia de Diamantes de Angola* 39: 1–231.
Koch, C., 1962a, 'The Tenebrionidae of southern Africa. XXXI. Comprehensive notes on the tenebrionid fauna of the Namib Desert', *Annals of the Transvaal Museum* 24: 61–106.
Koch, C., 1962b, 'Analysis of the Madagascan components of the subfamily Tentyriinae (Tenebrionidae, Coleoptera) with revisions of the generic systematics of the Asidini from Africa south of the Sahara and the African, Asiatic and Palaearctic Epitragina of Tentyriini', *Mémoires de l″institut de la scientifique de Madagascar* 13: 1–146.
Penrith, M.-L., 1986, 'Relationships in the tribe Adesmiini (Coleoptera: Tenebrionidae) and a revision of the genus *Stenodesia* Reitter', *Annals of the Transvaal Museum* 34(13): 275–302.
Penrith, M.-L. & Endrödy-Younga, S., 1994, 'Revision of the subtribe Cryptochilina (Coleoptera: Tenebrionidae: Cryptochilini)' *Transvaal Museum Monograph* 9: 1–144.
Penrith, M.-L., 1977, 'The Zophosini (Coleoptera: Tenebrionidae) of western southern Africa', *Cimbebasia Memoir* 3: 1–291.
Penrith, M.-L., 1979a, 'Revision of the western southern African Adesmiini (Col. Tenebrionidae)', *Cimbebasia A* 1: 3–94.
Penrith, M.-L., 1979b–1983, 'Revision of the Zophosini', Part 1–7: *Cimbebasia A,* (1979b) 1, 1–21; (1981) 2, 17–109; (1981) 3, 111–124; (1981) 4, 126–164; (1982) 5, 165–226; (1982) 6, 227–289; (1983) 7, 292–367; (1983) 8, 370–384; (1983) 9, 385–416; (1986) 10, 417–502.
Picker, M., Griffiths, C. & Weaving, A., 2004, *Field Guide to Insects of Southern Africa*, Struik Publishers, Cape Town.
Platnick, N.I., 1991, 'Patterns of biodiversity: tropical vs temperate', *Journal of Natural History* 25(5): 1083–1088, https://doi.org/10.1080/00222939100770701.
Polis, G.A., Barnes, J.D., Seely, M.K., Henschel, J.R. & Enders, M.M., 1998, 'Predation as a major cost of reproduction in Namib Desert tenebrionid beetles', *Ecology* 79(7): 2560–2566, https://doi.org/10.1890/0012-9658(1998)079[2560:PAAMCO]2.0.CO;2.
Mucina, L. & Rutherford, M.C. (eds.), 2006, The vegetation of South Africa, Lesotho and Swaziland, *Strelitzia* 19, South African National Biodiversity Institute, Pretoria.
Schawaller, W., 2007, 'A new myrmecophilous species of *Cimiciopsis* Koch from Namaqualand in South Africa with a stridulatory organ, and a checklist of the genera of Adelostomini (Coleoptera: Tenebrionidae)', *Annals of the Transvaal Museum* 44: 203–208.
Scholtz, C.H. & Holm, E., 1985, *Insects of southern Africa*, Pretoria Book House, Pretoria.
Wharton, M. & Robert, A., 1982, 'Species composition of and biological notes on Tenebrionidae of the lower Kuiseb River and adjacent gravel plain', *Madoqua* 13(1): 5–25.

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Distribution of *Mimosa diplotricha* in eastern and southern Africa and its socio-ecological impacts in northern Malawi

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Background: *Mimosa diplotricha* is an emerging or established weed in many parts of the world, including many countries in Africa, where it is impacting on biodiversity, crop and pasture production, and driving socio-ecological change.

Objectives: To establish the current distribution of *M. diplotricha* in eastern and southern Africa and its impacts on livelihoods in northern Malawi.

Methods: Records on current distribution were collected from roadside surveys, literature reviews and herbarium data. Household surveys were conducted in the Karonga District, Malawi, to understand its impacts on local livelihoods.

Results: *Mimosa diplotricha* is abundant in western Ethiopia, southern Tanzania, and northern and southeastern Malawi with isolated populations in western Rwanda, Burundi, Mozambique, and on the northern shores of Lake Victoria in Uganda. Most respondents said that *M. diplotricha* invasions were reducing the amount of grass and shrubs in rangelands, with over half saying it reduced crop yields. This invasive plant is also reducing the availability of medicinal plants and other natural resources.

Conclusions: *Mimosa diplotricha* has the potential to significantly expand its range in eastern Africa, and parts of southern Africa, and as such there is an urgent need to develop and implement an integrated management strategy, including biological control, to reduce the negative effects of this invasive plant on local livelihoods.

Disclaimer: These are the authors' views and not those of any institution/organisation

Introduction

People have been moving plants around the world for centuries for ornamental, medicinal, agro-forestry and other purposes (Pimentel et al. 2001). Only a small percentage of these introduced species have become invasive, having a negative impact on, among others, biodiversity, crop and/or pasture production, human and/or animal health, and water resources (Pimentel et al. 2001; Singh 1996; Tamado & Milberg 2000; Van Wilgen et al. 2008). Economic development can even be curtailed by the presence of invasive plant species, especially waterweeds, which can hamper hydro-electricity generation, bringing economic activity to a virtual standstill. As such, biological invasions are now considered to be among the most pressing issues facing the planet, especially in developing countries where the natural resource base on which millions of people depend is rapidly being eroded by the rapid proliferation of many invasive species (Shackleton et al. 2017a,b,c; Witt & Luke 2017; Witt et al. 2018).

The situation is exacerbated in developing countries because the rural poor don't have the means to control these rapidly expanding species (Witt & Luke 2017). To reduce the impacts of invasive species and contain their further spread, it is imperative that management interventions be developed and implemented. Failure to do so will make it virtually impossible for countries to meet many of their Sustainable Development Goals. In fact, Target 15.8 focusses only on invasive alien species; requiring countries to 'introduce measures to prevent the introduction and significantly reduce the impacts of invasive alien species on land and water ecosystems and control or eradicate the priority species by 2020'. One of the plant species having a significant impact on biodiversity and crop and pasture production at a global level, including Africa, is *Mimosa diplotricha* Sauvalle (Fabaceae; creeping sensitive plant), hereafter referred to as 'mimosa'.

Mimosa diplotricha as a global invader

Mimosa diplotricha is native to much of South and Central America, as well as the Caribbean (Holm et al. 1977; Parsons & Cuthbertson 1992). It has been introduced, either intentionally or accidentally, to a host of countries in Asia and Africa. It is a major weed in pastures, plantations and roadsides, and in some situations a serious pest in crops (Caunter & Shibayama 1999; Ogbe & Bamidele 2006; Sulaiman et al. 2004). More than 40 years ago it was already considered to be one of the 76 worst weeds in the world, having been recorded as a weed of 13 crops in 18 countries (Holm et al. 1977). Holm et al. (1979) regarded it as either a 'serious' or 'principal' weed in Borneo, Fiji, Malaysia, Melanesia, New Guinea, West Polynesia, Philippines, Taiwan, Australia and Indonesia. It is also a serious weed in the Pacific islands, South-East Asia, Mauritius and Nigeria (Waterhouse & Norris 1987).

In the Philippines, Malaysia, Thailand and Vietnam, mimosa is considered to be an important weed in upland rice (Caunter & Shibayama 1999). It is also one of the three main weed species of kale in Nakhon Pathom Province, Thailand (Pomprom et al. 2002) and a major weed of cornfields in Malaysia (Sulaiman et al. 2004). Mimosa densities of 630 000 plants per hectare reduced cassava root yield, 12 months after planting, by 80% in one study area in Nigeria (Alabi et al. 2001). In Benin City metropolis, Nigeria, where it has invaded farms, fallow fields and vacant land, it is regarded as the most noxious of all weeds (Ogbe & Bamidele 2006). In Papua New Guinea, mimosa has a direct negative impact on the growth, yield and harvesting of sugarcane. Harvesting crops by hand in fields invaded by mimosa is also particularly difficult and even harmful, especially in developing countries where this is a common practice and farmers have no protective gear, as the 'thorns can cause serious sores on humans' (Waterhouse & Norris 1987). Mechanical crop harvesters can also be jammed when used in invaded croplands (Parsons & Cuthbertson 1992).

Mimosa invasions also have a negative impact on pastureland, reducing livestock carrying capacities. Cattle ranches in the Markham Valley, Papua New Guinea (PNG), spend up to US$130 000 annually on the chemical control of this weed (Kuniata 1994), because it not only displaces valuable forage species but is also considered to be toxic to livestock (Gibson & Waring 1994; Waterhouse & Norris 1987). In Thailand, 22 swamp buffaloes died 18–36 hours after eating *M. diplotricha* var. *inermis* (Tungtrakanpoung & Rhienpanish 1992). There is also a report of *M. diplotricha* var. *inermis* poisoning of a two-year-old Jersey-cross heifer in India (Alex et al. 1991). Trials in Australia have demonstrated that this variety of mimosa is also toxic to sheep, and a report from Flores, Indonesia, suggests that it is toxic to pigs (Parsons & Cuthbertson 1992).

Mimosa can also change the structure and composition of natural vegetation by climbing over and smothering other plants (Schultz 2000). In western Australia, dense stands are adversely affecting the growth of native plant species (Werren 2001), posing a serious threat to the ecology of native plants and animals if allowed to spread further (Wilson 2004). It also constitutes a serious fire hazard, especially during dry periods when plants tend to die back (PIER 2008).

Very little is known about the distribution of mimosa in eastern and southern Africa, and particularly its socio-ecological effects in Malawi. This type of information is critical in guiding management decisions, especially with regard to preventing the further spread of this noxious weed and implementing control where it is already well established. This paper contributes to a better understanding of the distribution of mimosa and its impacts on livelihoods in northern Malawi.

Methods

Distribution of *Mimosa diplotricha* in eastern and southern Africa

Broad-scale distribution mapping of naturalised and invasive plants was undertaken across eastern and parts of southern Africa (Figure 1) from 2008 to 2018, in a similar manner to those undertaken by Henderson (2007), Rejmánek et al. (2016), Shackleton et al. (2017 a,b,c), Witt (2017), Witt & Luke (2017) and Witt et al. (2018). Roadside surveys are a relatively cost-effective way of producing a rapid and broad understanding of the distributions of invasive species, especially where

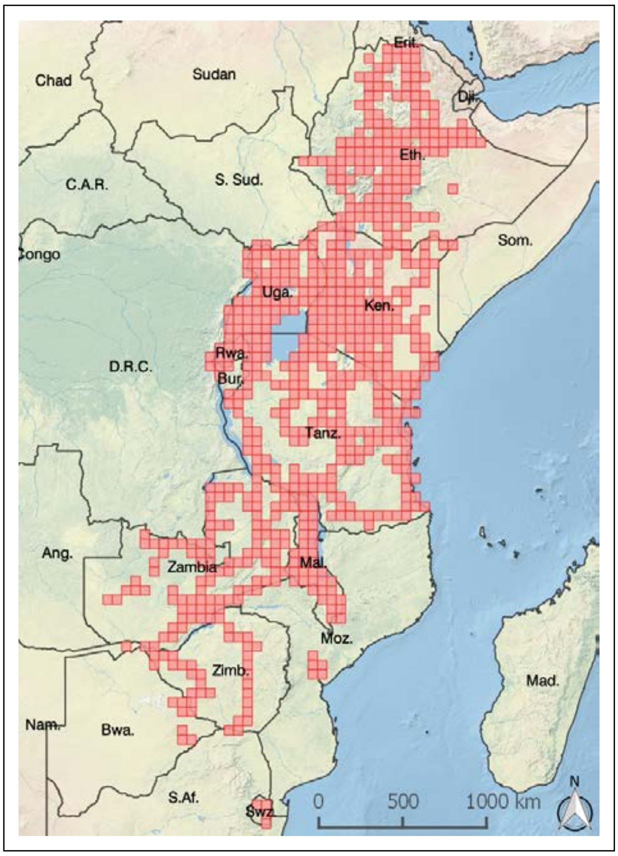

Figure 1: Map showing in red (~55 km × 55 km/half degree grid cells) the areas surveyed between 2008 and 2018 for *Mimosa diplotricha* species in eastern and southern Africa. Areas surveyed by others in eastern and southern Africa are not included.

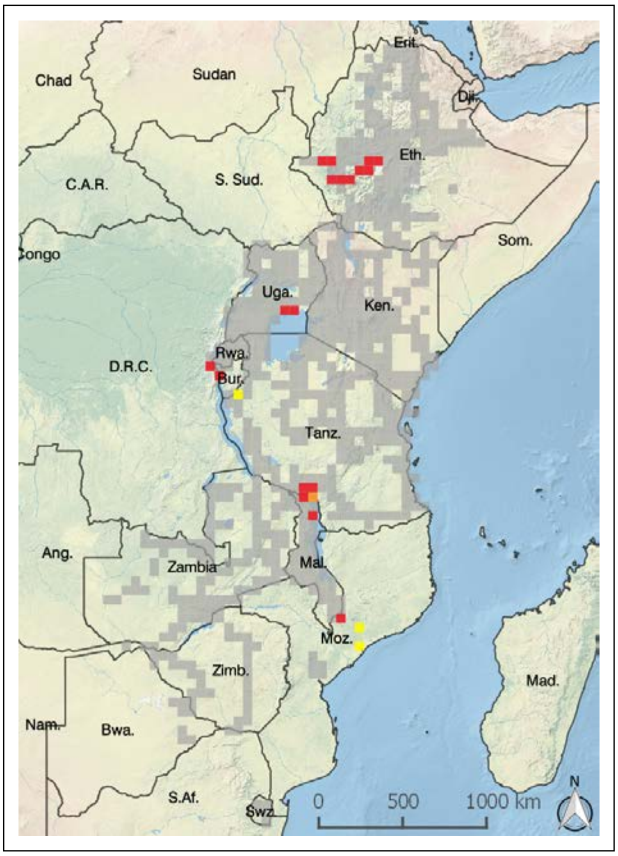

Figure 2: Map showing the current known distribution of *Mimosa diplotricha* in eastern and southern Africa (~55 km × 55 km/half degree grid cells) using data collected in this study and other sources of information. Grey grid cells show areas surveyed; red grid cells indicate areas where *Mimosa diplotricha* was found to be invasive (widespread and/or abundant); orange cells where it was present and/or naturalised; and yellow cells where it was recorded with no other information.

current information is scarce or absent. During these roadside surveys, the presence and status (naturalised or invasive) of *M. diplotricha* was mapped in Ethiopia, Kenya, Malawi, Eswatini, Tanzania, Rwanda, Uganda, Zambia, and parts of Botswana and Zimbabwe.

Lack of resources, insecurity and poor road access in some parts of these countries limited the extent of surveys. The presence of invasive alien plants (including mimosa) was noted in half-degree grid cells (~55 km × 55 km; Figure 2), but recorded presence does not imply full coverage, as the whole cell was not necessarily covered in the survey. It would also be extremely difficult and time consuming to record the exact location of every invasive plant seen, especially if it is growing some distance from the road. As such, coordinates, at or within 1 km of each locality where mimosa was found to be present, naturalised or invasive, as defined by Blackburn et al. (2011), were recorded using a hand-held GPS unit (Figure 2). We assumed that if mimosa was not seen within a grid square, during our surveys, that it was not present there. As such, it is therefore highly likely that we have under-represented the true distribution of mimosa in eastern and southern Africa.

Socio-ecological study site

To assess people's insights, understanding, and attitudes to the invasion by mimosa, we interviewed community members in Karonga District in northern Malawi (Figure 3). This district (9° to 10° S; 33° to 34° E), covering an area of 3 355 km², is bordered by Lake Malawi in the east, the Songwe River and floodplain in the north (border with Tanzania) and the Central African plateau and Nyika escarpment in the west and south (Chilima et al. 2006). The months from December to April are typically warm and wet with an average temperature of 24°C; cool and dry from May to August; and hot and dry from September to November (Chilima et al. 2006). The mean annual rainfall is more than 1 600 mm in the north and 800–1 200 mm in the south (Chilima et al. 2006). Soils are generally loamy and acidic to neutral in the north, and sandier and more acidic to alkaline in the south (Chilima et al. 2006).

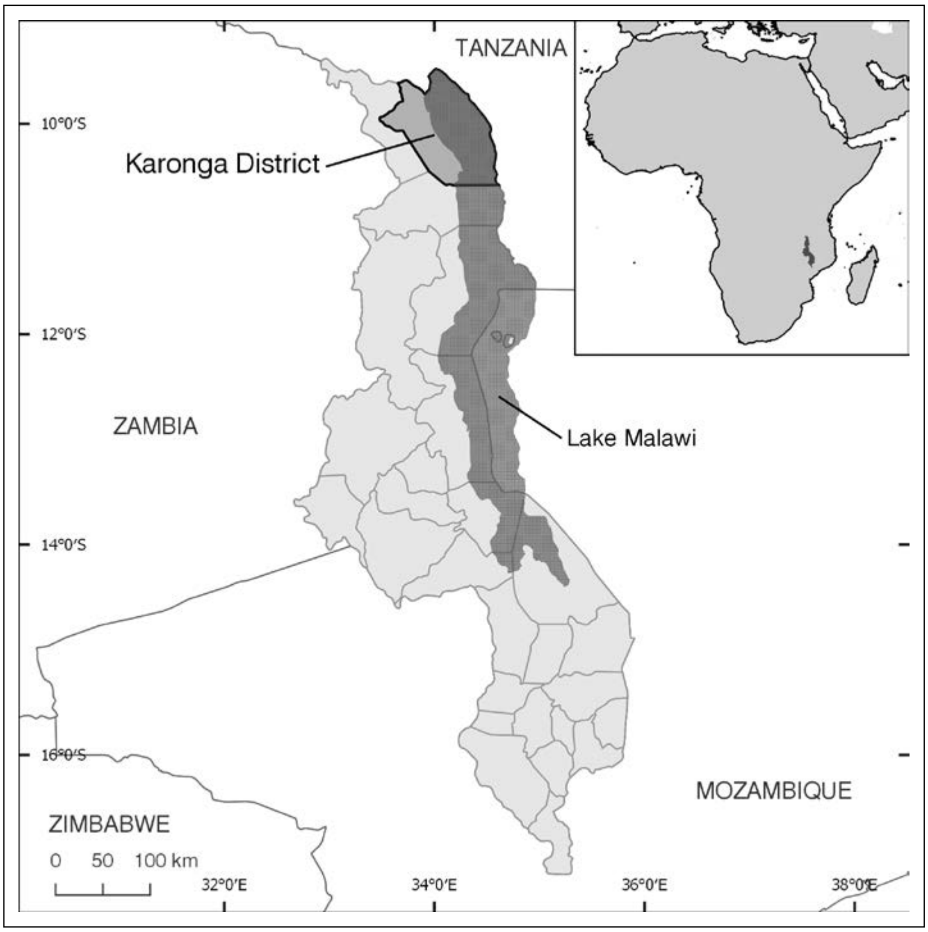

Figure 3: Map showing the location of Malawi in Africa (inset) and Karonga District in Malawi where the socio-economic surveys were undertaken.

The terrain is variable, with a flat coastal plain along the lake, which is dominated by croplands and mimosa invasions, rising to hills and the plateau (± 2 600 m a.s.l.) to the west. Despite high rates of deforestation, Karonga District is still largely dominated by miombo woodlands, which are dominated by trees in the genera *Brachystegia*, *Julbernardia* and *Isoberlinia*, with other tree species such as *Pterocapus angolensis* DC. (Fabaceae), *Albizia* spp. (Fabaceae) and *Afzelia quanzensis* Welw. (Fabaceae) (Missanjo et al. 2014). Rivers, which arise on the plateau in the west, are associated with dense vegetation and with swamps where they flow into Lake Malawi (Denys et al. 1999).

The people of Karonga District include several language groups, predominantly Tumbuka in the south and Nkhonde in the north, with a total population of about 365 000 people. The majority of residents are small-scale farmers with approximately 79 000 farming households (Government of Malawi/Ministry of Agriculture, Irrigation and Water Development 2016). An assessment of a community living in the south of the district found that only 3% of homes have electricity, 16% have piped water; the most common construction materials are burnt brick walls (59%), grass thatch roofs (57%) and mud flooring (76%) (Unknown 2019). The main sources of household income are farming (43%), regular employment (15%), trading (11%), casual labour (9%) and fishing (7%). A radio is owned by 62% of households, 52% own a clock or a watch, 44% have a bicycle and 19% own cattle (Unknown 2019). We are assuming that these figures will be similar for other communities living in Karonga District.

Livelihoods survey on local knowledge and perceptions of *Mimosa diplotricha*

We conducted interviews in 151 randomly selected households in areas with mimosa invasions, using semi-structured questionnaires. Surveys were conducted in 32 villages across Karonga District, to obtain as broad a representation as possible. We make the assumption that the impacts of mimosa in this area will be similar to those experienced elsewhere. All households on randomly selected roads in each village were interviewed by one of the co-authors. The head of the household or next oldest member of the family was interviewed in their local language. The questionnaires had four sections that covered (1) demographics of the respondent, (2) aspects of his/her knowledge and perceptions about the introduction and spread of mimosa, (3) perceptions and knowledge on the negative impacts and benefits of mimosa with a particular focus on crop and pasture production, and (4) perceptions and practices relating to the management of mimosa.

Results

Current distribution of *M. diplotricha* in eastern and southern Africa

Based on our surveys, mimosa is abundant in western Ethiopia, southern Tanzania on the northern shores of Lake Malawi, and northern and southeastern Malawi, with localised invasions on the northern shores of Lake Victoria in Uganda and in southeastern Rwanda (Figure 2). It has been recorded in Burundi, on the border with Rwanda (GBIF 2017), Madagascar (GBIF 2017) and Mozambique (Flora of Mozambique 2017; GBIF 2017; M. Hyde pers. comm., 19 December 2018), with no records for South Africa (Henderson 2007; GBIF 2017; L. Henderson pers. comm., 10 January 2019), Zimbabwe or Zambia (Flora of Zimbabwe and Zambia 2017; GBIF 2017; M. Hyde pers. comm., 19 December 2018), Angola (Rejmánek et al. 2016; GBIF 2017), Botswana (GBIF 2017; K. Keotshepile [Peter Smith University of Botswana Herbarium], pers. comm., 15 January 2018), and Namibia (GBIF 2017; C. Mannheimer [Consultant Botanist], pers. comm., 20 January 2018). It was first recorded as present in East Africa in 1943 (Witt & Luke 2017), and in southern Africa, in Mozambique, in 1949 (Figueira 2017).

Based on the Köppen Climate Classification it is currently present in areas with a Tropical Savanna (Aw) (southwestern Ethiopia, Rwanda, Burundi, Mozambique and southeastern Malawi), Tropical – Rainforest (Af) and Tropical – Monsoon (Am) (northern shores of Lake Victoria), and Temperate – Dry winter – Hot summer (Cwa) (northern Malawi) climates (Peel et al. 2007). Invasions in southern Tanzania are a mix of Aw and Cwa (Peel et al. 2007).

Socio-demographic characteristics of the surveyed households

Of the 151 individuals interviewed, 91% were male, and the mean (± SD) age of respondents was 43 ± 14 years. Just over half (57%) of respondents had a primary school education and the majority were farmers (84%). Every household owned livestock, with the majority owning at least two or more cattle while only 62 households owned goats, none had sheep and only two had pigs. Most (62%) farmers grazed their livestock within 1 km of their homes. Depending on the availability of grazing some farmers would move their livestock to grazing lands further afield but then only once in every three or more months. All respondents were also involved in crop production with the primary crops grown being rice (100%), cassava and maize. Just over a quarter (26%) of respondents had fields between 2 and 3 acres (0.8–1.2 ha.) in extent, followed by 23% who had 1 to 2 acres (0.4–0.8 ha.) of land under crop production.

Local knowledge of Mimosa diplotricha *presence and introduction in Malawi*

About 58% of respondents said that mimosa was first seen in the area where they live more than ten years ago, while 22% noticed it three to five years ago, and a smaller percentage (6%) for the first time in 2018. This supports the view of most (71%) respondents who claim that mimosa density and distribution is increasing, with 97% saying that it is already present in areas where they graze their livestock. According to 61, 31 and 8% of the respondents less than 25, 26–50 and 51–75% of grazing land is currently invaded, respectively, with most invasions occurring along rivers, in croplands and on roadsides. Most (86%) of those interviewed were unsure as to why mimosa was introduced with just over 41% saying that it was spreading naturally, with 30% having no idea as to how it found its way to the areas where they reside. Some (8%) felt that it had been accidentally introduced with machinery during road construction while others (20%) thought that livestock were spreading the seeds. The fact that 63% of respondents did not find any use for the plant is an indication that intentional spread by people is unlikely or very low based on the fact that only 19% of those interviewed used the plant for medicinal purposes.

Socio-ecological stressors

Residents of Karonga District, Malawi, face a number of challenges. Livestock production is severely compromised by the prevalence of diseases and insufficient grazing, of which the latter could be further compromised by the prevalence of unpalatable plants, including weeds. However, only 14 respondents were of the opinion that weeds and other poisonous plants were having a significant impact on grazing. *Mimosa diplotricha* was considered to be the worst weed in rangelands, closely followed by its congener, *Mimosa pigra* L. (Fabaceae) another introduced invasive plant native to South America (Table 1). In crop production areas *M. diplotricha* was also considered to be the worst weed, followed by *Striga* spp. (Orobanchaceae), *M. pigra* and *Bidens pilosa* L. (Asteraceae) (Table 1).

Impacts of *Mimosa diplotricha*

Based on responses, mimosa has a significant impact on livelihoods. All respondents said that mimosa hampered

Table 1: The percentage of respondents ($n = 151$) who selected a particular weed species as having the largest negative impact on either rangelands or crops in Karonga District, Malawi

Species	Family	Rangelands (%)	Croplands (%)
Ageratum conyzoides	Asteraceae	2	1
Bidens pilosa	Asteraceae	14	7
Tithonia diversifolia	Asteraceae	2	1
Xanthium strumarium	Asteraceae	2	1
Trichodesma zeylanicum	Boraginaceae	3	3
Sedges and grasses	Cyperaceae and Poaceae	-	9
Mimosa diplotricha	Fabaceae	28	33
Mimosa pigra	Fabaceae	22	15
Hyptis suaveolens	Lamiaceae	9	5
Striga spp.	Orobanchaceae	6	22
Argemone mexicana	Papaveraceae	3	1
Datura stramonium	Solanaceae	5	1
Lantana camara	Verbenaceae	1	-
Stachytarpheta spp.	Verbenaceae	1	-

the movement of people and livestock. In addition, the majority of those interviewed said that invasions reduced the abundance of grasses and shrubs, while 50% of respondents said that it had a negative impact on trees (Table 2; Box 1). In contrast, only 8% of respondents said that mimosa was reducing the abundance of medicinal plants, with the majority (89%) being unaware of any negative impacts. Despite its negative impacts on livestock fodder (grass and shrubs) only 48 and 25% of respondents felt that invaded rangelands had a negative impact on cattle or goats, respectively, with only 25% saying it resulted in weight loss in their cattle. Just over 50 and 73% of respondents said that they had seen cattle eat mimosa flowers and leaves, respectively, with a much lower figure recorded for goats (flowers, 33%; leaves, 38%). Over half (56%) of the respondents said that mimosa had a negative impact on crop yields while only 21% felt that it increased yields.

Box 1: Quotes from villagers on the impacts of Mimosa diplotricha *invasions in Malawi*

'Mimosa is a very serious weed, fast spreading and if not removed timely cause huge losses in crops, it can be so helpful if ways of eradicating it completely can be found.'

'If mimosa is cut and burnt it improves soil fertility and any crop grown in those soils grows with vigour. However, it is a serious weed if left uncontrolled.'

'If chemicals to eradicate mimosa could be found it would be very helpful.'

'Mimosa has caused a lot of challenges; it grows fast and needs to be controlled almost every day, if you fall sick you won't harvest anything.'

'Mimosa causes a lot of losses in crops and our livestock have difficulties in finding pasture as it has covered most valuable pasture lands.'

'In 2015, I was in hospital with my son, mimosa took over my rice garden and I harvested nothing.'

Management of *Mimosa diplotricha*

Just over one-quarter of respondents actively managed mimosa in grazing lands while 97% tried to control it in croplands. Slashing (16%) was the most common control method used in rangelands followed by burning (7%). In croplands just over half (54%) used a hoe or pick to remove mimosa, followed by slashing (21%) and hand pulling (18%). Over half (59%) of respondents said that they paid individuals to help them clear mimosa from their croplands. Of these 39% said they paid others between US$14 and US$28 to clear an acre (0.405 ha.) of land while 11% said that they paid around US$56 per household. Fifty-seven per cent of those that use herbicides spend between US$14 and US$70 on chemicals per year. If mimosa were not controlled, maize and rice

Table 2: The percentage of respondents ($n = 151$) who regarded the effect of *Mimosa diplotricha* on a particular issue as either positive or negative, or who had no opinion on the issue, in Karonga District, Malawi

Issue	Percentage who regarded effect as a cost (%)	Percentage who regarded the effect as a benefit (%)	Percentage who thought it had no effect, or who did not know (%)
Grass	99	1	-
Shrubs	72	1	27
Trees	50	37	13
Water	7	3	90
Wildlife	-	1	99
Useful plants	8	3	89
Movement	96	0	4
Crop production	56	21	23
Cattle health	48	0	52
Goat health	25	0	75
Drive human relocation	32	0	68
Green manure	-	7	93
Medicinal plant	-	19	81
Garden plant	-	5	95
Hedge plant	-	5	95

Table 3: The percentage of respondents ($n = 151$) who used particular management practices to control *Mimosa diplotricha* in rangelands and croplands in the Karonga District, Malawi

Management practice	Rangelands (%)	Croplands (%)
Burning	7	1
Chemical control	0	3
Hand pulling	0	18
Hoeing	0	54
Nothing	72	3
Slashing or cutting	16	21
Ploughing	5	1

losses would be greater than 75% according to 72% and 79% of respondents, respectively. The majority of respondents all felt that their lives would be better if mimosa was not present, with over 80% saying that there would be increased grazing, improved livestock health and improved crop yields.

Discussion

Mimosa diplotricha occurrence

The field surveys, literature reviews and questionnaires indicate that *M. diplotricha* is relatively widespread with localised invasions in a number of countries in eastern Africa but less so in southern Africa, with significant invasions only in the north and southeast of Malawi with some records from Mozambique, although the latter was never surveyed during this study, so its current status there is unknown. In Ethiopia, the plant is abundant along roadsides from Wolisso to Jimma in the southwest. In many areas the plant is scrambling over the edge of the road, blocking footpaths and waterways (Wakjira 2011). According to community members in Merewa Kebele in Kersa Woreda, Ethiopia, the plant has been invading roadsides for the past three to five years with road construction contributing to its spread (Wakjira 2011). In our study only eight per cent of respondents said that road construction contributed to the spread of mimosa with 41% saying that it was spreading naturally and with 31% being unsure.

Respondents to the questionnaire indicated that it is still spreading in Malawi, an indication that it has the potential to spread even further in the region as a whole, especially into tropical and sub-tropical regions within eastern and southern Africa. A CLIMEX ecoclimatic model developed by T. Beale (unpublished) indicates that most of Uganda, Rwanda and Burundi have climates suitable for mimosa invasions while northern Tanzania and its coastline, extending across much of the interior towards Malawi, also appear to be a good climatic match. Our surveys further support the model by indicating that the southwest of Ethiopia and northern and southeastern Malawi are climatically suitable. Areas in which no mimosa was seen during surveys, such as the southwest of Kenya and its coastline are also a climatic match and as such likely to be invaded should mimosa be introduced and establish there. Much of the coastline of Mozambique, extending inland to southern Malawi, and the northeastern coast of South Africa also appear to be climatically suitable, together with the whole of the eastern Madagascan seaboard (T. Beale unpublished). It is unlikely to establish and proliferate in Zimbabwe, Botswana, Namibia and Zambia, but much of northern Angola appears to be a good climatic match. Low temperatures are also likely to limit the species, which means that high-lying areas/regions are unlikely to be invaded although it has been found at 1500–2000 m above sea level (Henty & Pritchard 1973; Kostermans et al. 1987).

Impacts of *Mimosa diplotricha*

Malawi is one of the poorest countries in the world with 50.7% of the population living below the poverty line, and 25% of those living in extreme poverty (Ministry of Finance, Economic Planning and Development 2017). More than 80% of the population live in rural areas and are dependent on subsistence agriculture to survive. Food security is compromised by a number of factors, such as frequent droughts and crop pests. The impacts of crop pests such as the fall armyworm (*Spodoptera frugiperda* J.E.Smith, 1797; Noctuidae) are well documented, but there is little data on the impacts of invasive plants, which are often ignored because their impacts on rangelands or crop production are not that direct or conspicuous. This study has suggested that an invasive plant such as *M. diplotricha* can have significant negative cross-cutting impacts on a range of sectors including biodiversity, and crop and pasture production.

Impacts of *M. diplotricha* on biodiversity have not been well documented with the exception of a few studies in India (Jayasree 2005; Vattakavan et al. 2002). Jayasree (2005) found that the smothering efficiency of mimosa increased from about 14 to 38% over a three-year period contributing to a 21% decline in grass cover, and a reduction in the occurrence of other broad-leaved weeds. Similar impacts on grass cover were reported by Basu & Ghosh (2003) with Vasu (2003) finding that mimosa inhibits the growth of especially grasses. This supports the findings of our study where the majority of respondents reported a significant decline in the abundance of grasses and shrubs in invaded areas. The absence of wildlife in most areas outside of protected areas meant that almost all respondents in Malawi did not know of any impacts on wildlife. However, mimosa invasions in the Kaziranga and Orang National Parks in India are displacing important forage species for the endangered greater one-horned rhino and other wildlife species (Lahkar et al. 2011; Vattakavan et al. 2002). Mimosa also blocks the trails used by elephants and rhinos (Vasu 2003). Invasion of protected areas in India by mimosa and other weeds 'is the biggest challenge in terms of habitat conservation' and as such poses a significant threat to protected areas in Malawi. As in India, invasions may threaten black rhinos, which were reintroduced to Liwonde National Park and Majete Wildlife Reserve, after the last rhino in Malawi disappeared from the Mwabvi Game Reserve in the late 1980s.

A reduction in the amount of forage will obviously also contribute to a reduction in livestock carrying capacities. It is considered a major threat to livestock pastures in Australia (Groves 1991), some Pacific islands (Swarbrick 1989), Papua New Guinea (Henty & Pritchard 1973), and the Philippines (Holm et al. 1977). In Vietnam, respondents also said that mimosa displaced other valuable forage species, reducing the amount of grazing available for livestock (Ta Thi Kieu Anh [Biodiversity Conservation Agency, Vietnam], pers. comm., 15 January 2015). However, 52 and 28% of respondents in Malawi said that its presence in grazing lands had no impact on goats and cattle respectively, while approximately one-quarter of respondents were unsure of its impact. That said, 25 and 19% of respondents said that its presence did result in weight loss in cattle and goats respectively, which we assume is a result of a reduction in the amount of available forage. On the other hand mimosa may be consumed by livestock and as such could be an alternative fodder source.

In our study respondents said that they had seen cattle and goats eat the mimosa flowers and leaves with no ill effects, with the exception of a few who noticed that livestock developed diarrhoea after consumption. This is contrary to other studies, which found mimosa to be toxic to livestock (Alex et al. 1991; Gibson & Waring 1994; Li et al. 1996; Rajan et al. 1986; Shridhar 2017; Tungtrakanpoung & Rhienpanish 1992; Waterhouse & Norris 1987). Shridhar (2017) reported on 16 cows and ten buffaloes that had accidentally consumed mimosa leaves. Of the 26 animals, 22 exhibited perineal oedema and died within 14 days of consumption (Shridhar 2017). Mimosine, which is present in mimosa and other legumes such as *Leucaena leucocephala* (Lam.) de Wit (Fabaceae) is said to be the cause of toxicity in animals (Mishra et al. 2002). Immature leaves, mature leaves and stems, flowers, and seeds of *M. diplotricha* contain 9.88, 6.32, 5.01, and 3.3% mimosine respectively, which is similar to that found in *L. leucocephala* although the seeds of leucaena contain significantly more mimosine (Jayasree 2005). There can also be significant differences in mimosine content among different cultivars of leucaena (Chathurvedi & Jha 1992; Forrajes, Chongo & Seull 2003), although this has not been determined for invasive *M. diplotricha* sub-species or varieties. Ubani et al. (2000) found that mimosine at more than 1% concentration in livestock feed is toxic to livestock. This was confirmed by Yami et al. (2000) who found that that diets containing 0.75% mimosine could be fed to goats without adverse effects. Kumar

Figure 4: *Mimosa diplotricha* invasions in southern Tanzania (top row), northern Malawi (middle row), and western Ethiopia (bottom row).

and Sharma (1997) found that 1.6% mimosine in livestock feed is safe for goats. Consumption of mimosa leaves and flowers by cattle and goats in Malawi, as reported by respondents, may be at levels below this, hence the fact that no significant livestock deaths have been reported in our survey. However, as mimosa invasions increase in extent and density, displacing more valuable forage species, consumption of mimosa by livestock is bound to increase, which may result in a significant increase in livestock deaths. However, the recurved spines/thorns on mimosa mean that livestock are often reluctant to feed on it anyway, and they usually avoid the large stands (Waterhouse & Norris 1987), which may also limit consumption.

Mimosa diplotricha also has a significant impact on crop production (Figure 4). Rajkowa et al. (2003) reported serious negative impacts of the weed on crop ecosystems and plantations such as tea, coffee, coconut, rubber and pineapple. It is considered to be one of the most important weeds of rubber in Indonesia, Malaysia and Papua New Guinea (PNG); coconut in Sri Lanka and PNG; sugarcane in Taiwan, Australia, India and the Philippines; tomato in the Philippines; lychee in Thailand; cassava, soyabeans, maize, apple, citrus and tea in Indonesia; banana and tea in India; and abaca (*Musa textilis* Née; Musaceae) and pineapple in the Philippines (Aliudin & Kusumo 1978; Groves 1991; Holm et al. 1977; Muniappan & Viraktamah 1993; Suwanarak 1988; Wong 1975). It is a weed of lowland rice in Indonesia, the Philippines, Thailand and Vietnam; of dry-seeded rice in the Philippines; and of upland rice in Indonesia, Laos, the Philippines, Thailand, and Vietnam (Kostermans et al. 1987; Moody 1989). It is potentially the worst weed in plantations and arable lands of Fiji, and the Philippines (Holm et al. 1977). It has also been recorded as having a negative impact on cassava root yield (Alabi et al. 2001), and on the height of okra (*Abelmoscus esculentus* (L.) Moench (Malvaceae) plants in Nigeria (Alabi & Makinde 2002). This agrees with our findings with more than 50% of respondents reporting a reduction in crop yields as a result of mimosa invasions, especially on the yields of the three most commonly grown crops, namely rice, cassava and maize. This reduction in yields can be ascribed to the smothering habit of mimosa, and the fact that it is allelopathic. Jayasree (2005) reported that incorporation of mimosa, at increasing concentrations, either directly into the soil, as a mulch, or as a water extract application, all significantly reduced rice and cowpea seed germination. Although rice heights were enhanced with increasing rates of mimosa concentrations incorporated into the soil, the opposite was true for mulching and water extraction while all three methods of application had negative impacts on cowpea height (Jayasree 2005).

Management of *Mimosa diplotricha*

Mimosa diplotricha has the potential to spread over much of the region and as such there need to be increased efforts to stop or inhibit further spread, and to reduce densities where it is already present. In Malawi there is little current effort to manage mimosa in rangelands, with manual removal being the most commonly used methodology in croplands. Cutting or slashing of plants in croplands is a practice used by 21% of the respondents despite this practice being largely ineffectual because plants vigorously regrow from the root crown (Parsons & Cuthbertson 1992; Waterhouse & Norris 1987). Hand pulling of young plants is practiced by 18% of respondents in croplands, just like farmers do in Indonesia (Suryatna & McIntosh 1982), despite the tiny thorns having the potential to cause injuries (Waterhouse & Norris 1987; Alabi et al. 2001). Just over 54% of respondents in Malawi said that they used a hoe or similar to uproot/remove plants in croplands. This practice appears to be very effective, consistently giving the highest cassava root yield in Nigeria (Alabi et al. 2004). In Vietnam 96% of landowners use sickles or similar to remove the above-ground parts of the plant and hoes to remove the root crown following by drying and burning (Ta Thi Kieu Anh [Biodiversity Conservation Agency, Vietnam], pers. comm., 15 January 2015). Many of these interventions were not seen to be effective, and often merely stimulated seed germination.

Mimosa diplotricha can also be effectively controlled using herbicides (Parsons & Cuthbertson 1992) although very few respondents in Malawi said that they used herbicides because of the associated costs. A similar survey in Vietnam revealed that only 4% of respondents used chemicals, despite it being the only effective control method (Ta Thi Kieu Anh [Biodiversity Conservation Agency, Vietnam], pers. comm., 15 January 2015). Another issue, which applies to much of Africa and even Asia, is the fact that no herbicides are registered for use against mimosa. For example, in Nigeria there are no effective herbicides for control of mimosa in cassava fields (Alabi et al. 2004). However, in countries such as Australia, foliar applications of herbicides containing the active ingredients picloram, clopyralid and fluroxypyr are known to be effective although they need to be applied on a regular basis to control seedlings (Parsons & Cuthbertson 1992). Dicamba (500g/L) is also recommended and should be applied in a foliar spray at 2g/L of water, fluroxypyr (333g/L) at 1g/L of water and glufosinate ammonium (200g/L) also at 1g/L of water (J. Vitelli pers. comm., Department of Agriculture and Fisheries, Queensland Government, Australia, 12 June 2016; Witt & Luke 2017). Pre-emergence chemicals such as atrazine + 2,4-D mixtures or tebuthiuron can be used, but they only remain active for a few months (Waterhouse & Norris 1987).

Biological control remains the most cost-effective intervention for resource poor farmers. *Heteropsylla spinulosa* Muddiman, Hodkinson & Hollis (Psyllidae), an agent collected on *M. diplotricha* in Brazil in 1982, causes stunting and distortion of the leaves and may prevent flowering due to the toxic effects of its saliva. Soon after its release in Australia there was a dramatic reduction in the growth of *M. diplotricha* and seed production was reduced by over 88% (Lockett & Ablin 1990). It has subsequently been released in Western and PNG (Kuniata 1994) where it is now established, and should be considered for release in Malawi. Despite the success of this agent elsewhere, any management strategy should incorporate the biocontrol agent in combination with other methodologies such as physical and chemical control, and in some cases also fire.

To further enhance the management of mimosa, concerted efforts need to be made to build additional awareness as to the negative impacts of this serious weed in the region. This should include further research on its negative impacts, especially with regard to livestock production, where its apparent toxicity has not yet been reported by the majority of livestock owners. There also needs for increased awareness as to best management practices, and support from local communities and government officials for the introduction of the biocontrol agent *H. spinulosa*. It should also be noted that areas cleared of *M diplotricha* may be invaded by other invasive species already present in Malawi. These may include *M. pigra*, *Prosopis juliflora*, *Lantana camara* and *Hyptis suaveolens* (L.) Poit. (Lamiaceae). In fact, *H. suaveolens*, an emerging weed in Malawi, is regarded as one of the world's most noxious weeds (Padalia, Kudrat & Sharma 2013) and was ranked very highly in our surveys in terms of its negative impacts. In Australia it is considered to pose the greatest threat to rangeland biodiversity. In order to be more effective in managing these and other invasive species we need to develop coordinated national and regional integrated management strategies. Failure to address current barriers to invasive species management will exacerbate poverty in Malawi, and the region as a whole.

Conclusions

Mimosa diplotricha is already present in a number of countries in eastern and southern Africa and likely to expand its range, exacerbating biodiversity loss and further reducing crop yields and rangeland productivity.

To inhibit its further spread, it is imperative that communities be informed as to its negative impacts and best management practices.

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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. conducted the weed surveys and contributed to writing up the article. L.C. conducted the socio-economic surveys. T.B. was responsible for map development. W.N. conducted the weed surveys and was responsible for data entry.

References

Alabi, B.S. & Makinde, E.A., 2002, 'Effect of population levels of thorny mimosa on okra (*Abelmoschus esculentus* L.) growth and yield', *Moor Journal of Agricultural Research* 3(1): 54–58.

Alabi, B.S., Ayeni, A.O., Agboola, A.A. & Majek, B.A., 2001, 'Giant sensitive plant interference in cassava', *Weed Science* 49: 171–176, https://doi.org/10.1614/0043-1745(2001)049[0171:GSIIC]2.0.CO;2.

Alabi, B.S., Ayeni, A.O., Agboola, A.A. & Majek, B.A., 2004, 'Manual control of thorny mimosa (*Mimosa invisa*) in cassava (*Manihot esculenta*)', *Weed Technology* 18,1: 77–82, 10.1614/0890-037X(2004)018[0077:MCOTMM]2.0.CO;2

Alex, P.C., Rajankutty, K., Valsala, K.V. & Nair, K.N.M., 1991, 'Mimosa poisoning in heifer', *Journal of Veterinary and Animal Science* 22(1): 134–l36.

Aliudin & Kusumo, S., 1978, 'Testing the effectiveness of several herbicides in an apple orchard', *Bulletin Penelitian Hortikultura* 6: 35–42.

Basu, N.K. & Ghosh, S., 2003, 'Management of Mimosa species at Kaziranga National Park', *National Seminar on Alien Invasive Weeds in India*, April 27–29, 2003, AAU, Jorhat, Assam, Abstract 51.

Blackburn, T. M., Pyšek, P., Bacher, S., Carlton, J.T., Duncan, R.P., Jarošík, V., Wilson, J.R.U. & Richardson, D.M., 2011, 'A proposed unified framework for biological invasions', *Trends in Ecology & Evolution* 26: 333–339, DOI: 10.1016/j.tree.2011.03.023.

Caunter, I.G. & Shibayama, H., 1999, 'Bioherbicide studies in south east Asian countries', *Marine Highland Bioscience Central Report* 11: 67–73.

Chathurvedi, O.P. & Jha, A.N., 1992, 'Studies on allelopathic potential of an important agroforestry species', *Forest Ecology and Management* 53: 91–98.

Chilima, B.Z., Clark, I.M, Floyd, S., Fine, P.E.M. & Hirsch, P.R., 2006, 'Distribution of environmental mycobacteria in Karonga District, Northern Malawi', *Applied and Environmental Microbiology* 72(4): 2343–2350, DOI: 10.1128/aem.72.4.2343-2350.2006.

Denys, C., Chitaukali, W., Mfune, J. K., Combrexelle, M., & Cacciani, F., 1999, 'Diversity of small mammals in owl pellet assemblages of Karonga District, northern Malawi', *Acta Zoologica Cracoviensia* 42(3): 393–396.

Figueira, R. 2017, IICT Herbário LISC. Version 4.2. Instituto de Investigação Científica Tropical. Occurrence dataset https://doi.org/10.15468/iinlqm accessed via GBIF.org on 2019-05-01.

Flora of Mozambique, 2017, viewed 01 March 2017, from https://www.mozambiqueflora.com/.

Forrajes, D., La, 0.0., Chongo, B. & Seull, I., 2003, 'A note in chemical composition of six ecotypes of *Leucaena leucocephala*', *Cuban Journal of Agricultural Science* 37(1): 51-54.

GBIF (Global Biodiversity Information Facility), 2017, *Mimosa diplotricha* C. Wright ex Sauvalle GBIF Backbone Taxonomy. Checklist dataset https://doi.org/10.15468/39omei, viewed 6 May 2019, from https://www.gbif.org/species/2969352.

Gibson, T.A. & Waring, S.A., 1994, 'The soil fertility effects of leguminous ley pastures in north-east Thailand I. Effects on the growth of roselle (*Hibiscus sabdariffa* cv. *Altissima*) and cassava (*Manihot esculenta*)', *Field Crops Research* 39: 119–127.

Government of Malawi/Ministry of Agriculture, Irrigation and Water Development, 2016, *Karonga Agricultural Development Division*, viewed 6 May 2019, from http://www.agriculture.gov.mw/Profiles/KARONGA%20ADD%20INFORMATION%20FOR%20WEBSITE.pdf.

Groves, R.H., 1991, 'A short history of biological invasions of Australia', in R.H. Groves & F. DiCastri, (eds.), *Biography of Mediterranean Invasions*, pp. 59–63, Cambridge University Press, New York.

Henderson, L., 2007, 'Invasive, naturalised and casual alien plants in southern Africa: A summary based on the South

African plant invaders atlas (SAPIA)', *Bothalia* 37: 215–248. https://doi.org/10.4102/abc.v37i2.322.

Henty, E.E. & Pritchard, G.H., 1973, 'Weeds of New Guinea and their control' *Lp, Papua New Guinea: Department of Forests, Division of Botany, Botany* Bulletin 7.

Holm, L. G., Plucknett, D. L., Pancho, J. V. & Herberger, P. D., 1977, *The World's worst weeds: distribution and biology*, Honolulu, HI, University Press of Hawaii.

Holm, L.G., J.V. Pancho, J.P. Herberger & D.L. Plucknett., 1979, *A geographical atlas of world weeds*, J. Wiley, New York.

Jayasree, P. K., 2005, 'Biology and management of *Mimosa invisa* Mart.in Kerala', PhD thesis, Kerala Agricultural University, India.

Kostermans, A.J.G.H., Wirjahardja, S. & Dekker, R.J., 1987, 'The weeds: description, ecology and control' in M. Soerjani, A.J.G.H., Kostermans & G. Tjitrosoepomo, (eds.), *Weeds of rice in Indonesia,* pp. 24–565, Balai Pustaka, Jarkata, Indonesia.

Kumar, G.V.P.P.S.R. & Sharma, A., 1997, 'Genotoxic effects of subabul (*Leucaena leucocephala*) in goats', *Indian Journal of Dairy Science* 50(5): 376–383.

Kuniata, L. S., 1994, 'Importation and establishment of *Heteropsylla spinulosa* (Homoptera: Psyllidae) for the biological control of *Mimosa invisa* in Papua New Guinea', *International Journal of Pest Management* 40 (1): 64–65. https://doi.org/1080/09670879409371855.

Lahkar, B. P., Talukdar, B.K., & Sarma, P., 2011, 'Invasive species in grassland habitat: an ecological threat to the greater one-horned rhino (*Rhinoceros unicornis*)', *Pachyderm* 49: 33–39.

Li, Z., Wu, Y.H., Diao, X.P. & Wu, J.J., 1996, 'Cases of mimosa poisoning in camels', *Chinese Journal of Veterinary Science and Technology* 26(11): 38–39.

Lockett, C.J. & Ablin M.P., 1990, '*Heteropsylla* sp. – a biological control agent for giant sensitive plant (*Mimosa invisa* Mart.) in north-eastern Queensland', in J.W. Heap (ed), *Proceedings of the 9th Australian Weeds Conference Adelaide, Australia*. *Crop Science Society of South Australia*, pp. 529, viewed 6 May 2019, from http://caws.nzpps.org/awc/1990/awc199015291.pdfMendoza, S.P. Jr, 1978, 'Weed management in pineapple', *Weed Control in Tropical Crops Symposium, Manila*, 147-148.

Ministry of Finance, Economic Planning and Development, 2017, 'Economic Development Document for Malawi', Lilongwe, Malawi.

Mishra, J.P., Vaithiyatiathan, S. & Jakhmola, R.C., 2002, 'Mimosine toxicity in animals' *The- Blue Cross Book* 18: 5–7.

Missanjo, E., Kamanga-Thole, G., Mtambo, C. & Chisinga, O., 2014, 'Evaluation of natural regeneration and tree species diversity in Miombo woodlands in Malawi', *Journal of Biodiversity Management and Forestry* 3(3): 1–4. https://doi.org/10.4172/2327-4417.1000127

Moody, K., 1989, *Weeds reported in rice in south and southeast Asia*, International Rice Research Institute, Manila, Philippines.

Muniappan, R. & Viraktamath, C.A., 1993, 'Invasive alien weeds in the Western Ghats', *Current Science*, 64(8): 555–558.

Ogbe, F.M. & Bamidele, J.F., 2006, 'Incidence and spread of an invasive weed, *Mimosa invisa* Mart. in Benin City Metropolis, Nigeria', *International Journal of Botany* 2(3): 336–339, https://doi.org/10.3923/ijb .2006.336.339.

Padalia, H., Kudrat, M., & Sharma, K. P., 2013, 'Mapping subpixel occurrence of an alien invasive *Hyptis suaveolens* (L.) Poit. using spectral unmixing technique', *International Journal of Remote Sensing*, 34: 325–340, https://doi.org/10.1080/01431161.2012.714003.

Parsons, W. T., & Cuthbertson, E. G., 1992, *Noxious weeds of Australia*, Inkata Press, Melbourne.

Peel, M.C., Finlayson, B.L. & McMahon, T.A., 2007, 'Updated world map of the Köppen-Geiger climate classification', *Hydrology and Earth System Sciences* 11: 1633–1644. https://doi.org/10.5194/hess-11-1633-2007.

PIER (US Forest Service, Pacific Island Ecosystems at Risk), 2008, viewed on March 2018, from http://www.hear.org/pier/.

Pimentel, D., McNair, S., Janecka, J., Wightman, J., Simmonds, C., O'Connell, C., Wong, E., Russel, L., Zern, J., Aquino, T.& Tsomondo, T., 2001, 'Economic and environmental threats of alien plant, animal and microbe invasions', *Agriculture, Ecosystems and Environment*, 84:1–20.

Pomprom, T., Hayes, M. & Saridnirun, P., 2002, 'Competition and control of weeds in kale leaf crop', *Kasetsart Journal of Natural Science* 36(1): 1–10.

Rajan, A., Manomohan, C.B., Valsaia, K.V., Sreekumaran, T., Lalitha, C.R., Ramachandran, K.M. & Nair, 1986, 'Experimental studies on the toxicity of the plant *Mimosa invisa* Mart. *inermis* Adlb. in calves' *Kerala Journal Veterinary Science* 17(1): 91–98.

Rajkhowa, D.J., Barua, I.C., Kandali, R., Yaduraju, N.T. & Deka, N.C., 2003, 'Agrobiology and management of Mimosa spp', *National seminar on alien invasive weeds in India*, April 27–29, 2003, AAU, Jor~at, Assam, p.35.

Rejmánek, M., Le Roux, J.J., Huntley, B.J. & Richardson, D.M., 2016, 'Rapid assessment survey of the invasive plant species in western Angola', *African Journal of Ecology* 55: 56–69, https://doi.org/10.1111/aje.12315.

Schultz, G.C., 2000, 'Creeping sensitive plant (*Mimosa invisa)' AgNote/ Northern Territory Australia*, 493, p. 2.

Shackleton, R.T., Le Maitre, D.C., Van Wilgen, B.W. & Richardson, D.M., 2017a, 'Towards a national strategy to optimise the management of a widespread invasive tree (*Prosopis* species; mesquite) in South Africa', *Ecosystem Services* 27B: 242–252, https://doi.org/10.1016/j.ecoser.2016.11.022.

Shackleton, R.T., Witt, A.B.R., Aool, W. & Pratt, C., 2017b, 'Distribution of the invasive alien weed, *Lantana camara*, and its ecological and livelihood impacts in eastern Africa', *African Range and Forage Science* 34(1): 1–11, https://doi.org/10.2989/1 0220119.2017.1301551.

Shackleton, R.T., Witt, A.B.R., Nunda, W. & Richardson, D.M., 2017c, '*Chromolaena odorata* (Siam weed) in eastern Africa: distribution and socio-ecological impacts', *Biological Invasions* 19: 1285–1298, https://doi.org/10.1007/s10530-016-1338-4.

Shridhar N.B., 2017, 'Toxicity episodes of *Mimosa invisa* in cattle and buffaloes', *Toxicology International* 24, 2, DOI: 10.22506/ti/2017/v24/i2/162430.

Singh, S.P., 1996, 'Biological control' in R.S. Paroda & K.L. Chadha (eds.), *50 Years of Crop Science Research in India*, pp. 88–116. Indian Council of Agricultural Research, New Delhi, India.

Sulaiman, G., Hussein, M.Y. & Idris, A.B., 2004, 'Abundance and parasitism on the egg masses of the Asiatic corn borer *Ostrinia furnacalis* in weedy and weed free corn fields of

Malaysia', *International Journal of Agricultural Biosciences* 6(1): 36–38.

Suryatna, E.S. & McIntosh, J.L., 1982, 'Weed control in a shifting cultivation and permanent agriculture', *Biotropical Special Publication* 15: 63–73.

Suwanarak, K., 1988, 'Effectiveness of certain herbicides in litchi (*Litchi chinensis* Sonn.)', *Weedwatcher* 6(7): 6.

Swarbrick, J.T., 1989, 'Major weeds of the tropical South Pacific', in *Proceedings of 12th Asian-Pacific Weed Science Society Conference*, *Seoul, Korea, Asian-Pacific Weed Science Society* 1: 21–30.

Tamado, T. & Milberg, P., 2000, 'Weed flora in arable fields of eastern Ethiopia with emphasis on the occurrence of *Parthenium hysterophorus*', *Weed Research* 40: 507–521.

Tungtrakanpoung, N. & Rhienpanish, K., 1992, 'The toxicity of *Mimosa invisa* Mart. var. *inermis Adelbert* to buffaloes', *Buffalo Bulletin* 11(2): 30–31.

Ubani, O.N., Tewe, 0.0. & Aken'ova, M.E., 2000, 'Seasonal variation in mimosine in five accessions of *Leucaena leucocephala* in south west Nigeria', *Tropical Science* 40(4): 184–187.

Unknown, 2019, 'Karonga HDSS, Malawi', viewed 6 May 2019, from https://docsbay.net/Karonga-Hdss-Malawi.

Van Wilgen, B.W., Reyers, B., Le Maitre, D.C., Richardson, D.M. & Schonegevel, L., 2008, 'A biome-sale assessment of the impact of invasive alien plants on ecosystem species in South Africa', *Journal of Environmental Management* 89: 336–349.

Vasu, N.K., 2003, 'Management of invasive species at Kazaringa National Park', *National seminar on alien invasive weeds* in India, April 27–29, AAU, Jorhat, Assam, Abstract 10.

Vattakkavan, J., Vasu, N. K., Varma, S., Gureja, N. & Aiyadurai, A., 2002, *Silent stranglers: eradication of mimosa in Kaziranga National Park, Assam*, Wildlife Trust of India, New Delhi pp. 55.

Wakjira, M., 2011, 'An invasive alien weed giant sensitive plant (*Mimosa diplotricha* Sauvalle) invading Southwestern Ethiopia', *African Journal of Agricultural Research* 6(1): 127–131.

Waterhouse, D.F. & Norris, K.R., 1987, *Biological control: pacific prospects*, Inkata Press, Melbourne, pp. 454.

Werren G, 2001, Environmental weeds of the wet tropics bioregion: risk assessment & priority ranking, Report prepared for the Wet Tropics Management Authority, Cairns, viewed 6 May 2019, from http://www.rainforestcrc.jcu.edu.au/publications/research%20reports/ReportPDFs/Weeds.pdf

Wilson, N., 2004, 'Alert for mimosa watch in the North', *Northern Pastoral Region* 25(3): 3.

Witt, A.B.R. & Luke, Q., 2017, *Guide to the naturalized and invasive plants of Eastern Africa*, CAB International, Oxfordshire.

Witt, A.B.R., 2017, 'Use of non-native species for poverty alleviation in developing economies', in M. Vilà, P.E. Hulme (eds.), *Impact of Biological Invasions on Ecosystem Services*, vol. 12, pp. 295–310, Invading Nature – Springer Series in Invasion Ecology, Cham, Switzerland.

Witt, A.B.R., Beale, T., van Wilgen, B.W., 2018, 'An assessment of the distribution and potential ecological impacts of invasive alien plant species in eastern Africa', *Transactions of the Royal Society of South Africa* 73(3): 217–236, htpps://doi.org/ 10.1080/0035919X.2018.1529003.

Witt, A.B.R., Shackleton, R.T., Beale, T., Nunda, W. & Van Wilgen, B.W., 2019, 'Distribution of invasive alien *Tithonia* (Asteraceae) species in eastern and southern Africa and the socio-ecological impacts of *Tithonia diversifolia* in Zambia', *Bothalia* 49(1), a2356, https://doi.org/10.4102/abc. v49i1.2356.

Wong, P.W., 1975, 'Commercial development of Roundup post emergence weedicide as a one-shot treatment for control of lalang (*Imperata cylindrica*) in Malaysian rubber cultivation', *Proceedings of the Third Indonesian Weed Science Conference*, *Bandung*, 164–179.

Yami, A., Litherland, A.J., Davis, J.1., Sahlu, T., Puchala, R. & Goetsch, A.L., 2000, 'Effects of dietary level of *Leucaena leucocephala* on performance of Angora and Spanish doelings', *Small Ruminant Research* 38(1): 17–27.

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Coordinating invasive alien species management in a biodiversity hotspot: The CAPE Invasive Alien Animals Working Group

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Background: The effectiveness of invasive alien species management in South Africa, and elsewhere, can be improved by ensuring there are strong links and feedbacks between science and management. The CAPE Invasive Alien Animals Working Group (CAPE IAAWG) was established in 2008 to enhance co-operation among stakeholders such as implementing agencies and researchers, and thereby improve the management of invasive animals in the Greater Cape Floristic Region.

Objectives: In this article we highlight where and how the working group has advanced our understanding of research and the implementation of management objectives and consider the working group's successes and failures.

Methods: We analyse the attendance of meetings by different stakeholders and the frequency of discussion topics on meeting agendas throughout the sequence of meetings from 2008 to 2019. We document insights based on published accounts or the experiences of the authors from eight different management projects.

Results: Meetings are attended by stakeholders from NGOs, universities, and local, provincial and national government agencies as well as private individuals. Topics of discussion ranged from details of specific alien animal invasions (e.g. the House Crow in Cape Town), to considering the risks posed by broad groups (e.g. earthworms), to specific management techniques (e.g. guidelines for trapping invasive alien birds). Through the eight projects described here the CAPE IAAWG has: (i) contributed to capacity building through funding and advising on post-graduate research projects; (ii) provided ad hoc support to staff of agencies that implement invasive alien animal control; (iii) acted as a focal point for a community of practice that is supportive of decision making and policy development; and (iv) played a vital role in linking research, management and policy in a manner accessible to a broader range of stakeholders. The projects undertaken by the group reveal several lessons for managing invasive animals: (i) the importance of logistics and contract efficiency, (ii) the need for effective stakeholder engagement by the project team, (iii) the need to effectively address conflicts between role players, and (iv) the importance of including ethical and animal rights considerations in the decision making processes.

Conclusion: The CAPE IAAWG has been a valuable forum to improve management effectiveness and support implementation decisions. Due to its small cost and time footprint, the working group has remained viable and retained a core of committed members, ensuring ongoing institutional buy-in. The working group will remain successful so long as the group is supported by its members and their organisations.

Keywords: Status reporting; invasive alien species management; invasive alien species control; community of practice.

Introduction

The gaps between scientific research, development of policy and implementation of management measures are often significant, and can negatively affect conservation outcomes (Knight et al. 2008; Catalano et al. 2019). This issue has been analysed specifically in terms of how society responds to biological invasions (Esler et al. 2010; Foxcroft et al. 2020). Weak links and feedback loops between research and implementation are a major factor reducing the effectiveness of invasive alien species management in South Africa (van Wilgen & Wilson 2018). Various mechanisms and frameworks have been proposed to strengthen such links [also termed 'translational ecology' (Schlesinger 2010; Enquist et al. 2017)]. Different approaches to linking research, policy and implementation have several features in common; of particular interest in this work is the need to ensure that stakeholders are engaged and work together to co-produce knowledge that is meaningful and accessible to a broad range of stakeholders.

One approach to achieve the co-production of knowledge is to establish multi-stakeholder working groups that deal with specific or cross-cutting issues – these become communities of practice in which different role players interact intentionally to produce integrated environmental solutions that take ecological, social and political contexts into account. However, there is a consistent knowing–doing gap regarding such working groups (Esler et al. 2010; Foxcroft et al. 2020), and reducing this disjunction requires the analysis and documentation of the structure, functioning and outputs of existing groups to provide insights and ensure the continuation of working knowledge and communities of practice.

In this article, we provide a case study of the formation and continuation through more than ten years of a working group established to provide science- and evidence-based decision making support to the management of invasive alien animals in the Cape region. Specifically, we review the history of the Cape Action for People and the Environment Invasive Alien Animals Working Group (hereafter CAPE IAAWG or the working group), and consider its successes and failures. We outline a number of projects tackled by the working group, the key decisions made and the progress of each project to date, with the goal of highlighting where and how the working group has advanced our understanding of research and the implementation of management objectives.

Since its establishment in 2008, the members of the working group have engaged in collective identification of priority invasive animal species in the Greater Cape Floristic Region (GCFR), devised species-specific strategies for managing populations, and provided a platform for collaborative management. By integrating new and existing research findings, the working group has advanced its understanding of invasive alien species management through applied research and adaptive management and the sharing of these lessons with the working group. We argue that the working group model has been successful in facilitating work on invasive alien animals in the GCFR, and aim to document not only project successes, but also challenges and failures that provide direction for future alien animal control projects.

Methods of analysis

The authors analysed the agendas and minutes of all meetings of the working group since 2008. Attendees of meetings were classified by their host organisations, and organisations were clustered into sectors (local, provincial or national government agencies, non-government organisations (NGOs), private sector (e.g. a consultancy company) or research (e.g. university or research council). We used content analysis to analyse the frequency of discussion of taxonomic and selected other topics at full working group meetings and sub-group meetings. All analyses were conducted in R (R Core Team 2018) and plots produced using the *tidyverse* and *ggplot* packages (Wickham et al. 2019). Insights from management projects were based on published accounts or the experiences of the authors.

Background to the working group

The Greater Cape Floristic Region (GCFR) (Born et al. 2007) is a region of extraordinary floral diversity and endemism defined broadly by the winter rainfall areas of the southwestern Cape, which mostly overlaps with the Western Cape Province, South Africa (Figure 1). High levels of endemism are also present in several faunal groups [e.g. aquatic invertebrates (Colville et al. 2014)], making much of this region a UNESCO Natural World Heritage Site (https://whc.unesco.org/en/list/1007). Communities of practice have been

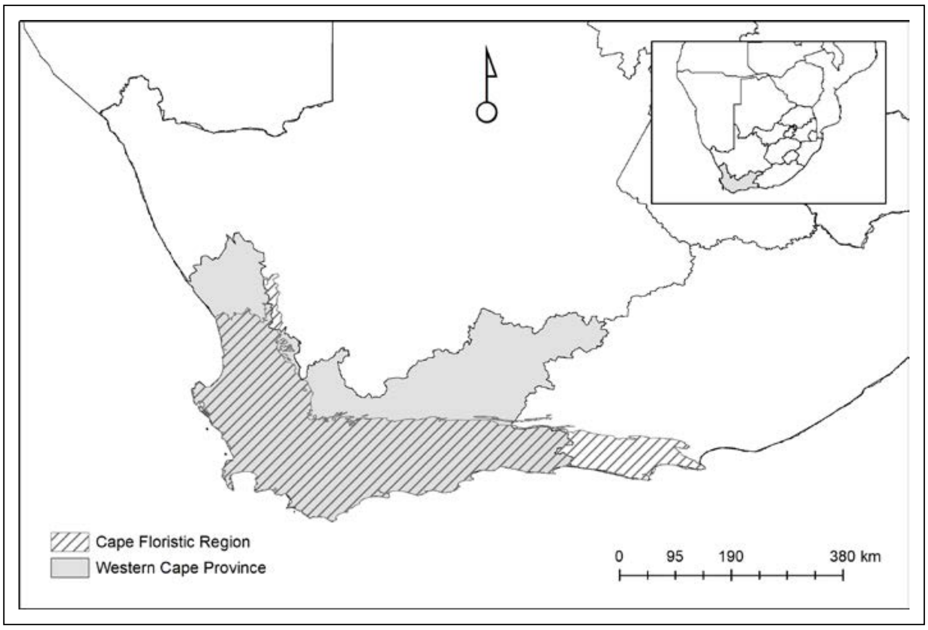

Figure 1. Boundaries of the Greater Cape Floristic Region, in which the CAPE Invasive Alien Animals Working Group functions.

integral to the conservation of the GCFR for over 40 years (Gelderblom & Wood 2018). Starting in 2000, the Cape Action Plan for the Environment (CAPE, later renamed Cape Action for People and the Environment) produced a 20-year plan to conserve the biomes of the GCFR. The planning process involved more than 100 organisations and individuals who worked together to draft a plan to ensure the conservation of the ecosystems of the Cape Floristic Region by integrating and coordinating the management of the landscapes and biodiversity in the long term. Since 2000, the CAPE plan has provided context, justification, funding and material resources for many conservation actions in the region. One of the major aims has been to integrate the work of organisations involved in conservation and biodiversity research in the GCFR and management of the GCFR, ensuring that they do not duplicate each other's work. In this paper, we argue that the CAPE IAAWG is a good example of the kind of impact the programme has had, and provides lessons of local, regional and international relevance.

In 2003, the Global Environment Facility (GEF) approved a grant to CAPE to develop a strategy for invasive alien species management in the GCFR. The strategy was developed under the auspices of CapeNature, by the CAPE Invasive Alien Species Task Team leader employed at CapeNature, who then joined the City of Cape Town in 2007 and continued to coordinate the development of the strategy. The overall goals of the strategy were to: (i) conserve ecosystems through collaborative efforts in combating the damaging impacts of invasive alien species in the region; (ii) develop early detection and rapid response capability; and (iii) increase awareness and understanding, by organisations and the public of the potential negative impacts of invasive organisms (see Appendix 1 for details). The CAPE Invasive Alien Species Strategy was finalised in 2008 with the vision that 'by 2020, the GCFR's economic, environmental and social assets are secure from the negative impacts of invasive alien species'.

The CAPE IAAWG was established by the CAPE Invasive Alien Species Task Team leader early in 2008. The group meets two to four times a year on average (Figure 2) for approximately four hours. In parallel, the CAPE Invasive Alien Plants Working Group was established (also in 2008), but that forum was dissolved after a few years due to overlap with other fora such as the Department of Environmental Affairs Working for Water Programme implementation fora. In contrast, the CAPE IAAWG brought together a range of animal taxon experts and institutions that did not otherwise interact closely and were enthusiastic about the potential for collaboration. The working group rapidly developed a novel and productive way of working, and the participants put in considerable effort to maintain their involvement (Adelle 2019).

The working group does not replace or duplicate activities under existing institutional arrangements or mandates, but is intended to address coordination of knowledge sharing; research, monitoring and evaluation; awareness, institutional arrangements and capacity-building; prevention, early detection and rapid response; policy and best practice (Appendix 2).

Composition

The CAPE IAAWG is composed of representatives of (i) national, provincial and local government agencies that have mandates related to invasive alien species control and management; (ii) private sector consultancies that take on contracts for invasive alien species control and management; (iii) tertiary education institutions and

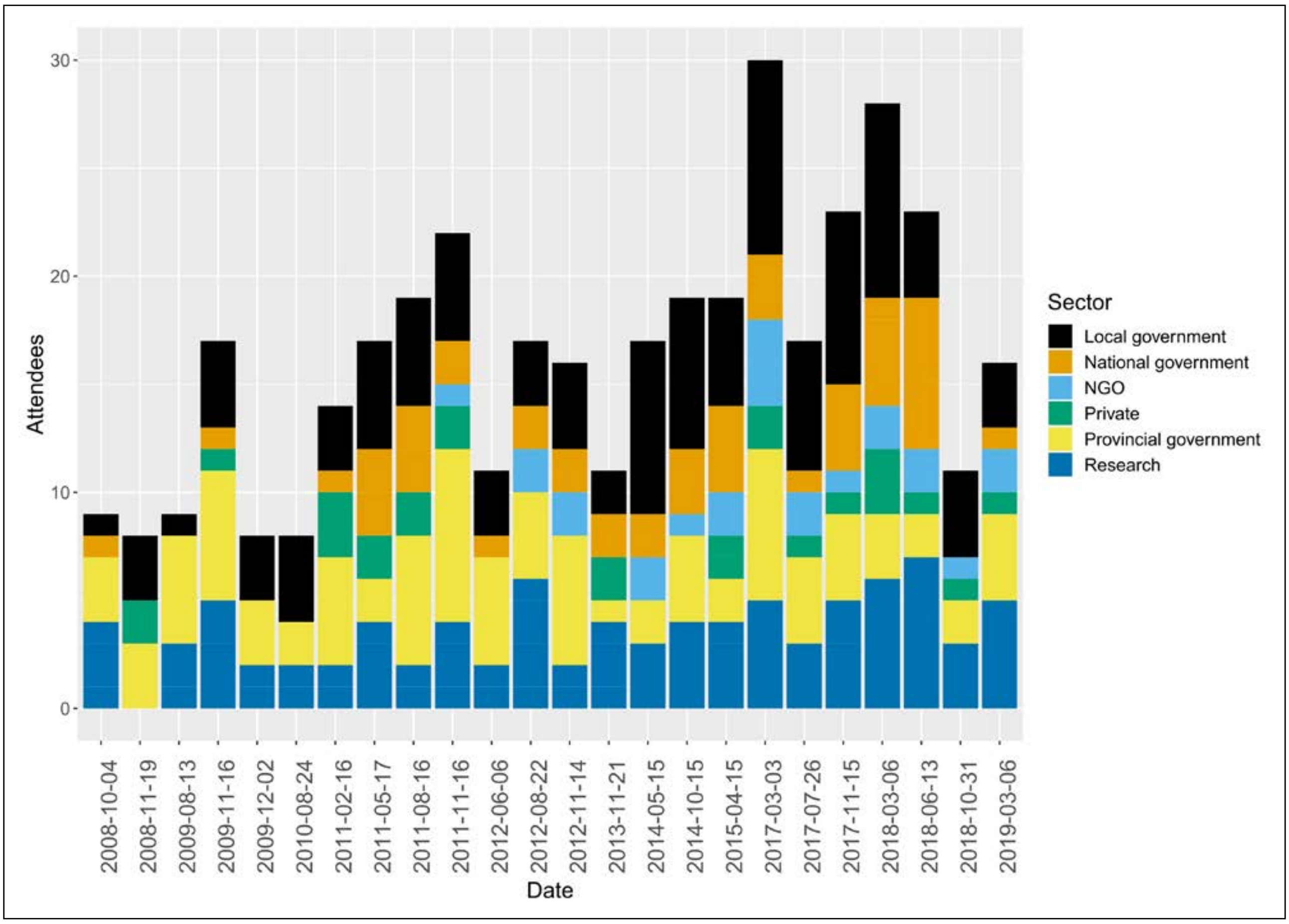

Figure 2. Time-line and turnover of sector participants in the CAPE Invasive Alien Animals Working Group. Since 2008 there have been 24 meetings, with between one and four meetings a year except for a hiatus in 2016. The number of participants has fluctuated between 8 and 30 people per meeting, and includes 102 unique individuals over time. The relative representation from six main sectors is shown here.

science councils that conduct research on alien and invasive animals; and (iv) NGOs with a regulatory or advocacy interest in alien and invasive animals (Figure 2; Appendix 3). The individual members have a diversity of roles in their home organisations, including local authority and provincial officials, national parks staff and environmental ministry officials, nature conservation scientists, university academic staff, post-doctoral researchers, post-graduate students, NGO staff, animal welfare officers and private consultants. The working group has a core of organisational representatives (Figure 2; Appendix 3) and other members are co-opted as and when required to represent specific interests or provide input on a particular subject or taxon. Therefore, the structure at a particular time reflects the workflow of specific projects and any issues being addressed by the working group. However, this structure also ensures a high level of continuity, with the group developing a common understanding and shared experience. The co-option of additional participants means that the core of member organisations and individuals has grown substantially over the years due to strong interest in the work of the group and the increase in number and complexity of the projects addressed by the group (Figures 2, 3). Permanent members sign the TOR on behalf of their organisations, which commit to implementing the recommendations of the CAPE IAAWG (Appendix 2). In turn, members are responsible for disseminating information from the working group to their structures or stakeholders.

The working group is formally located within the CAPE Programme, and its links to that programme are maintained through the co-chairperson of the working group who is employed by City of Cape Town and is a member of CAPE's Executive Committee. This linkage through the co-chair position ensures that the work of the group is integrated with other activities in the CAPE conservation programme. The CAPE IAAWG was originally chaired by the City of Cape Town Invasive Species Coordinator, but since 2017 it has been chaired jointly by senior staff at CapeNature and City of Cape Town's Biodiversity Management branch. The secretariat is supported by the City of Cape Town. This means that two of the largest implementers of invasive animal control projects in the GCFR have a shared official role in the working group.

Membership of the working group spans the Western and Eastern Cape provinces of South Africa, as both are host to significant areas of the GCFR (a small portion also enters the Northern Cape, but there have been no representatives from that province).

Expert sub-groups, such as the Guttural Toad Working Group, were formed when members felt it necessary to discuss issues in more depth than the broader group would be interested in or have time for, in particular to address particular problems or technical issues on a particular invasive alien species management project. These sub-groups meet separately when necessary and report back to the working group on their discussion and decisions.

Funding

The working group requires limited funding for its activities, as partner organisations cover the personnel and meeting costs. Although this has not been quantified, the continuity and regular attendance of the CAPE IAAWG indicates that member organisations experience benefits of participation (e.g. knowledge sharing, advice and information on best practice) that offset the costs of participation. The costs of the projects discussed at CAPE IAAWG meetings are, however, often substantial (Table 1). These projects have generally been funded by the South African government through its Department of Environment, Forestry and Fisheries (DEFF; formerly the Department of Environmental Affairs).

Links to legislation

When the CAPE IAAWG was inaugurated, there was no legislative framework that dealt with specific invasive alien animals and their control. Control projects carried out at the time were based on general commitments in high-level documents regarding a duty of care and the need to protect the environment for future generations (National Environmental Management Act, 1998 and the Constitution of South Africa, 1996); the legislative requirement to manage biological invasions (National Environmental Management: Biodiversity Act (NEM: BA), 2004; and provincial conservation ordinances). The need to actively control specific invasive animals was codified with the promulgation of the NEM: BA Alien & Invasive Species Regulations, 2014 and the accompanying Alien and Invasive Species Lists, which provide explicit requirements to control listed invasive

Figure 3. Taxa and topics discussed over time at the CAPE Invasive Alien Animals Working Group meetings. The bars span the period over which a species appeared on the agenda for discussion. Ticks on the X-axis represent the dates that meetings took place.

Table 1. The status of invasive alien animal management projects in the Greater Cape Floristic Region, where input was made by the CAPE IAAWG. Column names are based on the names used in the second national status report on biological invasions (Zengeya & Wilson in press) as per the indicators developed by Wilson et al. (2018), and where possible and indicated in alignment with the Darwin Core list of terms (Groom et al. 2019). The values are from the case studies or from the National Status Report on Biological Invasions (van Wilgen & Wilson 2018).

Taxon (dwc:venacularName)	**Native range**	**Introduction and pathways** (pathway)	**Status** [1] (dwc:degreeOf Establishment)	**Extent** (RangeFreeText)	**Abundance** (dwc:organism Quantity and dwc:organism QuantityType)	**Impact** [2] (impact EICAT or impact SEICATGlobal)	**Money spent** [3]	**Treatment and effectiveness**	**Role of CAPE IAAWG**	**Legislative category** [4] **and management goal**	**Key references**
House Crow (*Corvus splendens*)	Indian sub-continent	Probably as stowaways on ships, in Durban 1972, Cape Town 1979 (TransportStowaway: HitchhikersOnShip Boat)	Naturalised (C3)	Localised; several suburbs within the City boundary	High of 10 000 but down to ~310 by October 2018	Aggressive to people native biota, damage crops, spread disease. Scored as MO globally	ZAR 8 500 000	Multiple, focus on chemical bating and trapping, but House Crows can learn quickly. Different approaches will be needed at low densities	Review of methods and project progress. Support with ethical clearance	Category 1a. Nation-wide eradication	Oatley 1973; Berruti 1997
Guttural toad (*Sclerophrys gutturalis*)	Eastern Africa from Ethiopia to Eastern Cape, South Africa	First noted 2000 possibly deliberately as a pet. (Escape:Pet)	Invasive in a restricted area (D2), though native to wetter regions with summer rainfall	Largely confined to one suburb of Cape Town	Numbers of adults likely to be in the 10 000s	Scored MO in Western Indian Islands due to predation	ZAR 1 800 000	Spread slowed, population numbers reduced.	Review methods and project progress. Support with historical data. Initiated control operations. Formulated research project (PhD thesis) to inform control strategies	Listed as *Amietophrynus gutturalis* (now *Sclerophrys gutturalis*) as Category 1b in Western Cape, not listed elsewhere. Containment	Measey et al. 2017; Telford et al. 2019
Mallard Duck (*Anas platyrhynchos*)	North America and Eurasia	1940s possibly as a pet or for food. (Escape:Agriculture| Escape:Pet)	Invasive (E)	All provinces in SA; largely in human modified landscapes including peri-urban and agricultural areas	Population highly mobile into Fynbos Biome from other regions of South Africa. Resident population likely to be low 1000s	Hybridisation with native species (globally MR)	ZAR 1 024 000	Effective step-wise methodology, though conflicts with local people who feed the ducks (see text)	Recommendations on effective and ethical methods; a research Masters thesis addressed the evidence of hybridisation for the programme	Category 2 A Mallard Strategy for South Africa was drafted. Local extirpation	Stafford 2010, Stephens et al. 2020; SANBI unpublished
Feral pigs (*Sus scrofa*)	Eurasia	1920s–1930s for forestry pest control (Release:Biological Control)	Invasive (E)	Unknown but particular foci in Swartland/ Boland.	Unknown but likely to in 100s.	Many recorded impacts, including predation on the Critically Endangered geometric tortoise *Psammobates geometricus*. Globally EICAT MV & SEICAT MO	Unknown	Hunting and trapping. Effective for control. Local eradication requires sustained effort	Evaluation of progress. Discussion of new methods of control	Category 1b, not listed when not feral. Prevention of spread into protected areas and threatened species habitat.	Skead et al. 2011; Hofmeyr & Baard 2018
Invasive freshwater fishes [5]	Mostly North America	Many – see Weyl et al. 2020	20 species established (Weyl et al. 2014), of which 15 species are invasive (excludes translocated species)	All large river systems are invaded by multiple species.	Depends on inland water, but generally invasive fishes dominate ichthyofauna assemblages in invaded systems	Predation, competition and habitat degradation (carp *Cyprinus carpio*)	ZAR 3 000 000 for Rondegat project	Rotenone used successfully in discrete areas where natural dispersal of invader species can be controlled due to barriers. Manual control where feasible and cost effective	Discussion of methods and priority areas. Continuous reporting on progress	Various Limit spread to uninvaded waterways, prioritise a few stretches of water where extirpation is feasible, cost effective and desirable	Impson et al. 2013, Weyl et al. 2014, Ellender et al. 2017

Taxon (dwc:venacularName)	Native range	Introduction and pathways (pathway)	Status [1] (dwc:degreeOf Establishment)	Extent (RangeFreeText)	Abundance (dwc:organism Quantity and dwc:organism QuantityType)	Impact[2] (impact EICAT or impact SEICATGlobal)	Money spent [3]	Treatment and effectiveness	Role of CAPE IAAWG	Legislative category [4] and management goal	Key references
European shore crab (*Carcinus maenas*)	Europe	Not known, possibly through fouling or ballast water discharge (TransportStowaway: ShipBoatHullFouling / TransportStowaway: ShipBoatBallastWater). First detected in 1983 in Table Bay Harbour	Invasive (E), though currently restricted to transformed harbours	Table Bay and Hout Bay harbour and occasionally in intertidal area of the Cape Peninsula	Management in Hout Bay Harbour caught close to 40 000 individuals. Given the populations in Cape Town Harbour is at least an order of magnitude greater, the total population may be close to a million	Significant impacts elsewhere in the world, but negligible in South Africa to date	~ZAR 1 000 000	Crabs were caught in baited traps, although this might miss smaller and breeding crabs. Control using divers, traps for small individuals, and larval traps were trialled but were either too expensive or ineffective	Advice and support in getting approval for the method of euthanasia. Support for disposal of carcasses. Feedback to management and recommendations	Category 1b The trial management found nation-wide eradication is not feasible. In the absence of significant impacts and spread outside of the harbours, the recommendation is not to manage populations further. This would be reconsidered if spread is found during general marine invasions monitoring	Mabin et al. 2017, 2020
European paper wasp *(Polistes dominula)*	Europe, North Africa and temperate Asia as far east as China.	Unknown (In Cape Town since 2008)	Invasive (E)	Common throughout the City of Cape Town and the Boland	Unknown	Impacts on human health; other (e.g. biodiversity) impacts have not been established	ZAR 1 500 000 for both vespid species combined	Nest removal with pesticide fogging	Advice and support for teams; attempt to find other sources of support (e.g. Dept. of Health)	Category 1b Impact reduction	Benadé et al. 2014; Van Zyl et al. 2018
German wasp *(Vespula germanica)*	Europe, North Africa and temperate Asia as far east as China	Unknown (In Cape Town since 1974)	Invasive (E)	Most commonly found in the Southern region of the City of Cape Town and in Stellenbosch, Paarl, Banhoek and Franschhoek	Unknown	Impacts on human health; other (e.g. biodiversity) impacts have not been established	ZAR 1 500 000 for both vespid species combined	Physical nest removal	Advice and support for teams; attempt to find other sources of support (e.g. Dept. of Health)	Category 1b. Impact reduction	SANBI 2019
Earthworms	Various	Various, probably in contaminated soil, and perhaps as deliberate introductions for vermiculture.	It is not clear if there has been significant spread beyond cultivated areas (so B2–B3)	Widespread in transformed or previously transformed sites	Not known	Alien earthworms have caused profound ecosystem level changes (e.g. to forest dynamics) in areas where earthworms were previously absent (e.g. post-glaciation or islands like New Zealand)	No money spent on control	NA	Development of recommendations, support for research	None are listed. Research the risks and limit use in natural areas as a precaution	Plisko 2001; Plisko & Nxele et al. 2015; -Janion-Scheepers et al. 2016.

[1]Status as per Blackburn et al. (2011).
[2]Impact category is aligned to the IUCN's Environmental Impact Classification of Alien Taxa, Hawkins et al. (2015).
[3]Money spent is in South African Rand (ZAR) based on 2018 values.
[4]Legislative category is as per the NEM: BA A&IS Regulations (Department of Environmental Affairs 2014, 2016).
[5]Twenty species of invasive freshwater fishes established, with the most severe impacts caused by smallmouth bass (*Micropterus dolomieu*), spotted bass (*M. punctulatus*) and largemouth bass (*M. salmoides*) and rainbow trout (*Oncorhynchus mykiss*).

species. Category 1a and 1b species are prohibited from use and must be controlled [Category 1a species require compulsory control, which has been interpreted to mean that the goal is nation-wide eradication (Wilson et al. 2013)]; permits can be issued to use Category 2 species, although outside of the specified permits or conditions these are regarded as Category 1b; Category 3 species can be kept without the need for a permit under certain conditions, but further breeding is prohibited, and outside of captivity or cultivation they are also regarded as Category 1b. Proposed revisions to the regulations and lists were published in 2018 for public comment, but as of July 2020 these had not been promulgated, and so throughout this paper we focus on the lists and regulations as last amended in 2016.

Overview of projects tackled

This section describes eight projects established under the auspices of CAPE IAAWG, identifying key decisions and factors affecting the success of the project. Further details of the projects undertaken are shown in Table 1.

House Crows

A decision was made in 2003 to extirpate the expanding population in Cape Town, and a pilot project was initiated. The project soon stopped due to lack of funding, then restarted with a three-year grant from the United National Development Programme and then halted a second time due to concerns raised by the Society for the Prevention of Cruelty to Animals (SPCA) and the need to register the control agent DRC1339 (Starlicide) for use in South Africa (Yeld 2010). Two years of stakeholder engagement ensued before stakeholders could agree to attempt to extirpate the House Crows, and during this period (2009–2010) the population grew from an estimated 2 600 to 10 000 birds. However, the hiatus also proved to be a useful trial period for testing DRC1339 (Starlicide) and gathering the data necessary for the registration of this corvicide in South Africa. Support was also mobilised through media campaigns, petitions and complaints from residents in Nyanga, the high density residential area of Cape Town where House Crows were concentrated (see Measey et al. 2020). In 2011, the City Council approved ZAR200 000 to control House Crows and sent the project manager to Dar es Salaam, Tanzania for training on trapping techniques.

The ongoing campaign has significantly reduced the House Crow population with an estimated 310 crows remaining in October 2019. Implementation has cost over ZAR8 500 000, as the House Crows have proved to be very difficult to control; a number of approaches (mass baiting at roosting sites, spot baiting at feeding areas, trapping in pre-selected areas) yielded initial success, followed by diminished returns as populations shrank and House Crows learned to avoid each control approach. Alternative methods such as nest removal, egg collection and shooting have not yet been used due to high costs and security risks in the areas where the House Crows are found. At a CAPE IAAWG meeting in 2018, the group decided that additional funds should be sourced to increase the effort to reduce the House Crow population and investigate new techniques such as egg collection, egg substitution and falconry. On this basis, the City of Cape Town applied for and was granted additional funds from the National Resource Management Programme (NRMP) of the DEFF.

Guttural toads

The CAPE IAAWG was first made aware of the rapid expansion of the guttural toad population in Constantia, Cape Town, at a meeting in 2008. A mapping effort showed toads were present along a 3 km stretch of the suburban green belt in Constantia. The working group then made a decision to attempt eradication, in part as it was thought that guttural toads may pose a threat to indigenous Endangered western leopard toads (*Sclerophrys pantherina*) through competition or hybridisation (Measey et al. 2014, 2017, 2020). The eradication programme was coordinated by the City of Cape Town Invasive Species Unit. The first service provider was appointed by the City for the 2009/2010 breeding season, however, sustained control efforts only commenced in the 2011 breeding season. Initial efforts at awareness raising and control were met with both resistance and enthusiasm from residents who resented nightly calls as an invasion of privacy, or appreciated the help to remove noisy invaders, respectively (see Novoa et al. 2017). Access to residential properties was a major issue that required persistent efforts by service providers to win over property owners.

In 2014, the working group members initiated a post-graduate research project and various investigations in support of the guttural toad control project took place between 2014 and 2018. Population modelling by Vimercati et al. (2017a) showed that the extirpation of this population from Cape Town would require access to over 99% of residential properties. Between 2010 and 2019, guttural toad control teams in Cape Town were only able to access a fifth of the low-density residential properties located in Constantia and Bishopscourt (783 out of 3 935). At the time the toads were detected, there was no legal basis on which to access properties and remove toads if the owners were reluctant to allow or refused access. The NEM: BA Alien and Invasive Species Regulations of 2014 provides the legal basis to compel access to identified properties, but this facility has not been used yet and legal precedent still needs to be established. In all cases due process will need to be followed before access can be obtained and this increases the difficulty for the service providers. Concern has been expressed that access to properties will continue to limit the guttural toad control programme. While the need to access private property has been problematic in several other control campaigns [notably Mallard Ducks, *Anas platyrhynchos*, and House Crows] it has not formed as significant a barrier to operations as found in the guttural toad project (Vimercati et al. 2017a). The CAPE IAAWG has recognised the need for ongoing communication with initial stakeholders if eradication programmes are to succeed in the future.

Another important finding of the guttural toad research was that, in modelled populations, the removal of eggs and tadpoles had minimal impact on population numbers, and that it was more effective to remove juvenile and adult toads (Vimercati et al. 2017b). Thus, as a result of the research, project personnel have stopped removing eggs and tadpoles and focussed their efforts entirely on removal of juveniles and adults.

On 13 June 2018, the CAPE IAAWG acknowledged that extirpation of this population is currently unlikely, given the restricted access to private properties and insufficient removal rates. The CAPE IAAWG took the view, however, that containing the invasive population (i.e. focussing on monitoring and control at the known edge of the population) was worthwhile. Control measures during the breeding season are ongoing with some 10 517 adult toads having been removed to date (2010–2019) from 783 properties. City of Cape Town is committed to either containing or extirpating this population and received ZAR1 800 000 from DEFF: NRMP for this purpose in 2019.

Mallard Ducks

Mallard Ducks have been observed to mate with native Yellow-billed Ducks (*A. undulata*), and are considered a potential threat to the genetic integrity of this species (Dean 2000; Owen et al. 2006; Stafford 2010). The City of Cape Town and CapeNature for many years have recognised the importance of controlling Mallard Ducks. The Mallard Strategy for South Africa was drafted and a formal control campaign was started by the City of Cape Town following a decision at the CAPE IAAWG in November 2008. The campaign received a lot of public opposition from residents who enjoyed feeding the Mallard Ducks and considered them as pets. There was a lack of public awareness of the threat that Mallard Ducks pose to native birds (Stafford 2010) until the 'Save our indigenous water fowl' initiative was developed by the working group. This public education campaign shifted the focus of controlling Mallard Ducks to saving our indigenous duck species and thereby increased public understanding of the project's aims. The control project has experienced several delays in control efforts as a result of funding delays due to supply chain issues; for example, attempts to appoint a particular consultant as a sole provider of a specialist service in which they are very experienced often challenges financial rules and leads to extensive delays in project continuity. These disruptions allow population numbers to increase, reducing the efficiency of the control project. To date over 474 birds have been removed, and an estimated 200 remain in the target areas of Cape Town. The finally agreed method used to remove Mallard Ducks from residential areas involves the following step-wise methodology:

- Systematically traversing the target water bodies by rowboat and surrounding open natural space on foot to count all Mallard Ducks observed.
- Mapping and recording densities and distribution of Mallard Ducks observed per location in and around the target water bodies and surrounding open natural space.
- Habituating the ducks through prior baiting with bread.
- Hand-feeding the ducks with bread dosed with a sedative (Alphachloralose).
- Collecting the ducks once they had been sufficiently sedated (O'Hare et al. 2007); and
- Taking the ducks to an offsite location for euthanasia by a veterinarian (American Veterinary Medical Association 2013).

This process is monitored by the SPCA to ensure ethical treatment.

Samples from these Mallard Ducks were used to examine the degree and direction of genetic introgression with Yellow-billed Ducks (Stephens et al. 2020), which was shown to be primarily from Yellow-billed Ducks into Mallard Ducks, but is likely to lead to a hybrid population that is able to disperse widely.

Feral pigs

The potential control of the feral pig populations in the Western Cape was presented to CAPE IAAWG at its second meeting in November 2008 (Figure 3). Several populations of boars and hybrids between boars and feral domestic pigs are present in the province and those in the Kasteelberg and Porseleinberg districts of the Boland region are of most concern since they overlap the distribution of the geometric tortoise. CapeNature, the provincial conservation authority, produced a Feral Pig Management Strategy in 2011 with funding from DEFF: NRMP. The strategy covered effective control measures, monitoring the effects of control, and prevention of reintroduction, and presented a comprehensive communication strategy to raise awareness of the presence and negative impacts of feral pig populations. In 2014 feral pigs were listed as Category 1b invaders under NEM: BA.

Starting in 2014, CapeNature, with support and advice from the CAPE IAAWG, conducted a pilot trial of feral pig control by using baited traps and Judas pigs (collared sows that establish contact with and attract other pigs for trapping or hunting – McIlroy & Gifford 1997). This programme resulted in the removal of over 1 200 feral pigs from two populations in Kasteelberg and Porseleinberg, in addition to the feral pigs removed by land owners. The working group provided expert input and advice to the project manager during the planning and pilot project stages, and monitored project achievements during the operational phase. The oversight and involvement from the CAPE IAAWG resulted in additional funding being secured from DEFF: NRMP.

Invasive freshwater fishes

South Africa is one of six global invasive fish hotspots (Leprieur et al. 2008) and invasive fishes are the greatest threat to the native fishes of the Cape Fold Aquatic Ecoregion of South Africa, a conservation hotspot for freshwater fishes in southern Africa (Tweddle et al. 2009; Ellender et al. 2017; Weyl et al. 2020). The invasive alien species with the most severe impacts have been predatory species, especially three black bass species [smallmouth bass (*Micropterus dolomieu*), spotted bass (*M. punctulatus*) and largemouth bass (*M. salmoides*) (Weyl et al. 2014)], and rainbow trout (*Oncorhynchus mykiss*) in several headwater streams (Shelton et al. 2015). All four are native to North America, were imported into the Western Cape for angling purposes and are popular with the recreational angling sector and, hence, of significant socio-economic value (Ellender et al. 2014; see Weyl et al. 2020).

The river rehabilitation project, with its Rondegat River pilot project, was discussed at the first meeting of the CAPE IAAWG in 2008, and thereafter remained on the agenda as the project developed into a programme and gained further momentum after the successful treatment of the Rondegat River with rotenone in 2012 and 2013 (Impson et al. 2013). The project was the subject of an environmental impact assessment in 2007/8 and during this phase there was considerable controversy regarding the control of invasive fishes and the use of rotenone (Marr et al. 2012) including a number of critical articles in magazines, newspapers and blogs. Most criticism came from fly fishermen targeting *O. mykiss*, as one of the other four priority rivers had this species.

The support of this project by the CAPE IAAWG has played a major role in allowing it to proceed and achieve its goals, which included removal of the *M. dolomieu* from the treatment area followed by rapid recovery of the threatened native fish and aquatic invertebrate communities (Weyl et al. 2014; Bellingan et al. 2019). Due to the success of this initial project, CapeNature has since undertaken further invasive fish control projects and more are planned in the near future. The cost of the project, including co-funding and monitoring the ecological outcomes was estimated at ZAR3 300 000 (Impson et al. 2013). It is now considered a flagship restoration project in South Africa (Ellender et al. 2017; Zengeya & Wilson in press).

Marine invasions, including European shore crabs

The European shore crab *(Carcinus maenas)* was first discussed at the CAPE IAAWG in October 2014. In June 2014, a pilot management programme targeting the crab was initiated in Hout Bay harbour. Management ran until July 2015 and then the population was monitored for a further six months. The population was not extirpated, as there were several logistical challenges experienced during management including a hiatus in control efforts due to work contracts and research permits lapsing during the intervention, and because a molecular study (Mabin et al. 2020) showed the size of the population to be much larger than initially expected.

By providing links both to animal welfare organisations and to facilities for the disposal of carcasses run by the City of Cape Town, the CAPE IAAWG supported the project. However, with the formation of a National Marine Alien and Invasive Species Working Group, it is anticipated that the CAPE IAAWG will not have a major role in marine projects in future other than to note that research and implementation are continuing, and provide advice and support as appropriate.

Social wasps

The European paper wasp (*Polistes dominula*) and the German wasp (*Vespula germanica*) both have wide native distributions including Europe, North Africa and temperate Asia as far east as China. Records of *V. germanica* from Cape Town date back to 1974 when it was first recorded in the suburb of Newlands. Both wasp species were first discussed at a meeting of the CAPE IAAWG in May 2013, and thereafter both the City of Cape Town and Stellenbosch Municipality initiated a nest removal programme as a service to homeowners who were experiencing a problem with invasive wasps. By March 2019, a total of 12 375 *P. dominula* nests and 57 *V. germanica* nests had been removed. German wasps build nests in sites with more greenery, more readily available food and a more reliable water source, which are scarce within the urban boundaries. Thus, the bulk of German wasp removals have been in the south of the City; nests removed from the central urban areas have been much smaller as the resources in the area cannot support large nests. European paper wasps are less selective with regard to nest sites and thousands of nests have been reported and removed from the City. European paper wasps therefore pose a significant threat to human safety and have affected agricultural production and tourism by making some areas unsafe for humans. The CAPE IAAWG decided in 2017 that as the wasps cause more of a problem to human health than to the natural environment they should be managed by the Department of Health, in the same way that vermin control is carried out in the City. However, despite efforts to contact Department of Health representatives, and suggestions of initiatives, no resolution has been reached, and the problem continues to be managed by the City of Cape Town's Environmental Management Department. The CAPE IAAWG has supported applications for funding to the Departments of Agricultural and Health of the Western Cape, though as yet most funding is still either ultimately from the DEFF: NRMP and private landowners.

Currently, it is not feasible to eradicate *P. dominula* or *V. germanica* unless breakthrough technology such as gene drive mechanisms (currently being investigated in New Zealand) are developed into a viable control technique (Lester & Beggs 2019). The working group has suggested that there is reason to continue monitoring both species on the fringes of their invasive distributions to prevent further spread into other urban and rural areas.

Earthworms

Around 7.7% of global earthworm diversity is found in South Africa (Janion-Scheepers et al. 2016), but only alien species are used commercially in South Africa for waste recycling (i.e. vermi-composting), as bait for fishing, or for soil remediation. Several queries were raised with committee members as to the invasion risk posed by using alien earthworms for composting, particularly given the desire of many stakeholders to use worms as an 'environmentally acceptable' option for fertiliser production and waste disposal. The issue was discussed at consecutive meetings from late 2009 to 2012 and from 2015 to 2017, and a presentation was hosted on research on earthworms. The working group concluded that the spread of alien earthworms from vermi-compositing is not currently a major concern in the GCFR as most of the earthworms that are used for vermi-compositing thrive only in very wet, humic soils that are quite different from the nutrient poor, acid sands of the GCFR (except perhaps for the Afromontane Forest patches in some riverine areas). However, the working group noted that there is not enough information to adequately quantify the risk and recommended that, as a precautionary measure, alien earthworms should not be used in protected areas in the GCFR until such time as there is clear evidence that the risks of invasions are acceptable.

The requests for information from the CAPE IAAWG provided impetus for ongoing research on earthworms in South Africa. An earthworm sub-group was set up as a result of discussions at the CAPE IAAWG and SERG (Soil Ecosystem Research Group: SERG; http://sergsa.org/), which led to the development of standardised sampling protocols (e.g. Nxele et al. 2015), and now forms part of a larger collaboration on soil health. Earthworms continue to be discussed by the working group from time to time.

Other taxa

During the meetings of the CAPE IAAWG, many other taxa have been discussed (see Figure 3). Some discussions did not progress to action because the taxa were native (e.g. striped skink, *Trachylepis striata*), and/or had increased their ranges through anthropogenic habitat modification – see Essl et al. (2019) (e.g. Hadeda Ibis, *Bostrychia hagedash*, painted reed frog, *Hyperolius marmoratus* and Egyptian Goose, *Alopochen aegyptiaca*). Other discussions have not been followed up because the group decided that the benefit of control would be outweighed by opposition or a lack of support from the general public (e.g. Rock Dove, *Columba livia* and eastern grey squirrel, *Sciurus carolinensis*). Over time, changes in public opinion or the Regulations might mean there will be more support for control of such invasive animals in future. In future, novel techniques (like gene-drives) might change decisions by presenting inexpensive and effective management options. Based on the impacts that such species have, the CAPE IAAWG might then have a role to play (e.g. see Novoa et al. 2018).

Discussion and learning points

Logistical and contract difficulties

Local and provincial level implementing organisations (e.g. municipalities, provincial nature conservation agencies) have experienced challenges with implementing invasive alien species control projects due to limited funding availability and constraints due to funding cycles, as well as delays in procurement arising from internal supply chain management procedures. These issues have adversely affected the House Crow, guttural toad, invasive fishes and European shore crab projects (see above). Funds not being available at the beginning of the financial year when needed by the projects have, on several occasions, delayed control efforts. Flexibility and understanding from the working group and contractors have often ensured that the projects do not lose impetus, but the solution to such issues is essentially outside the scope of the working group. This situation is not unique to South Africa: Dana et al. (2019) analysed the factors that contributed to unsuccessful control operations conducted in Andalusia (southern Spain) from 2004 to 2018. The top factor determining project failure was the absence of funding at a crucial time for operational purposes, which occurred in 82% of cases analysed. Combined with other factors that frequently crop up in invasive species control operations (e.g. licencing of new control drugs), the unpredictability of funding renewals frequently leads to decreased operational efficiency. The question of whether funding is available at the time it is needed or whether contractors comply with supply chain management processes can halt the progress of a project during the onset of the breeding season when the animal is most detectable and demographically vulnerable. Clearly, a better alignment between the activities of the working group and relevant procurement policies is required. To give a specific example from the CAPE IAAWG projects, in 2011 and 2012, the lack of a signed contract or available funding at the beginning of the guttural toad breeding season between August and October, led to the loss of productive time (i.e. person days on the control operation), with concomitant feedbacks to operational efficiency. This could lead to the loss of skilled staff and to increased resources spent on training new operators and overall lengthened duration of the project.

Another area of concern is that the funding of projects is somewhat haphazard, more limited by bureaucratic processes than strategic prioritisation based on risk and impact. The National Invasive Alien Animals Forum was established in 2013 to assist DEFF with such issues. While the forum developed detailed recommendations for a funding allocation process (Jackson et al. 2015), these have not been implemented and the forum ceased activities in 2015.

Stakeholder engagement

Stakeholder engagement is a very important issue in the management of invasive alien animals. The CAPE IAAWG has applied the latest research to communication campaigns, checking that the message is scientifically defensible. The working group benefitted from the appointment of a communications expert who regularly attended meetings to ensure that projects were effectively communicated to stakeholders, including the media. The working group attempts to identify all important stakeholders for each project and involve them to decide on project feasibility or improve the operations of the project. In this way, a representative sample of local stakeholders is consulted early in the process to assess issues of concern and information regarding the history and nature of the particular biological invasion being investigated.

Stakeholder engagement is frequently perceived as too difficult to implement, too costly or too slow for management timeframes (Caceres-Escobar et al. 2019). However, systematic engagement processes have now been documented and have been employed with some success (Novoa et al. 2018). The initial phase of stakeholder identification does not replace the formal engagement process that occurs as part of most of the invasive species control projects. Formal engagement through focused meetings and invitations to participate in working group meetings has been exceptionally successful and has ensured that conflicts between stakeholders are resolved early on in the project life cycle. For example, regular participation of SPCA staff in the working group has improved project design and brought credibility to the programmes undertaken. Cape of Good Hope SPCA staff were present at the early Mallard Duck and House Crow control operations to ensure that the agreed upon procedures were implemented, and the ongoing interaction at working group meetings maintains an effective working relationship between the SPCA and the implementing agents.

Conflict between stakeholders

Conflict between stakeholders is a theme that has recurred with many of the invasions, and while some conflicts are commonplace and predictable, they have often surprised the working group members in their diversity (Shackleton et al. 2020; Gaertner et al. 2016). For example, conflicts have occurred around control options for invasive freshwater fish (smallmouth bass, rainbow trout); ownership of carcasses that result from a control programme (feral pigs); rights to own invasive alien species as domestic stock or pets (Mallard Ducks, guttural toads); the right to stock, hunt and fish alien species on private land (invasive freshwater fish, feral pigs); and the environmental benefits of invasive alien species (e.g. alien earthworms).

Input to regulations

The working group has not, to date, been formally involved in the identification and engagement of stakeholders, as such processes are the prerogative of individual organisations and projects. However, the working group offers a safe space to discuss issues and strategies, and by connecting multiple institutions it provides a route for communication in the initial stages of stakeholder engagement (Davies et al. 2020). We note that stakeholder engagement can shift not just opinions but the power of different stakeholders. In the case of the House Crow, it became clear through extension work that the crows were having significant negative impacts on less affluent communities in Cape Town, and this fact was used to counter-balance arguments that control of House Crows was ethically unacceptable (cf. Figure 7.3 in Wilson et al. 2017).

The control of invasive alien animals can be highly controversial and emotive, to the extent that project workers are physically threatened both when carrying out their jobs and in their private lives. The CAPE IAAWG cannot, of course, resolve this, but does offer a space to learn from previous experiences in the region and globally as to how to limit conflicts arising and diffuse them as necessary.

Ethics and animal rights

The control of animal species often relies on euthanising individual animals, although alternatives exist. For example, sterilisation and relocation can be an option, particularly for larger mammals. However, such options need to be weighed against the costs, and the difficulty and distress caused by trapping individuals, the cost of a veterinarian to conduct the procedure, and the subsequent logistical difficulty of relocating and rehabilitating animals in a way that ensures a continuing life of sufficient quality.

Many potentially effective campaigns have been hampered by concerns over ethical issues and the difficulty of reaching agreement on the correct method of euthanasia to be used. Appreciation that the health and welfare of individual animals are often compromised in the alien range raises the question whether these populations should be allowed to persist any longer. In the case of House Crows, ethical issues resulted in extensive delays (1–2 years) during which the population was exposed to the ongoing stresses of their novel environment, as well as the stress of the eventual control programme. In addition, the impacts of the crows on native birds via competition were extended in time. These two aspects demonstrate the increase in net harms (Fraser & MacRae 2011; Allen et al. 2019) attributable to project delays. Whether such debates can be reduced to an equation is a broad philosophical matter for society, but environmental management and conservation staff have to make hard decisions about how to act (or not act) to achieve environmental goals in the context of how different actions will affect both native and alien animals.

The representation of the national SPCA body on the CAPE IAAWG has significantly improved the appreciation of ethical methods that exist around the control of animals. The need to be alerted to these early on in the planning of any control operation is imperative, as is the rapid establishment of consensus on control options. When control methods e.g. drugs or pesticides that are not commonly used in the country are chosen, there can be considerable delay in registering and obtaining them (e.g. Starlicide; tricaine methanesulfonate [TMS]). Such issues could be avoided by a nationally agreed document describing best practice on how to euthanise different categories of animals. Such documents exist in other countries, and could easily be adapted for South Africa by the national environmental authority (i.e. DEFF).

The CAPE IAAWG has, to date, not been directly involved in determining which species should be listed and regulated under the NEM: BA A&IS Regulations. It did, however, provide written comments to DEFF on the proposed 2018 changes to the regulations and lists, as it is important for the CAPE IAAWG to speak for the particular community of practice that it represents. As the process for developing recommendations for listing is becoming clearer and more transparent [in particular through the Alien Species Risk Analysis Review Panel and the development of a risk analysis framework (Kumschick et al. 2018, 2020)], the CAPE IAAWG will in future play a more direct role in providing scientific advice to underpin whether and how invasive alien animal species should be controlled. Risk analyses that provide supporting evidence for the listing of several species have been discussed by the working group after approval by the Alien Species Risk Analysis Review Panel (e.g. the Pacific oyster, *Crassostrea gigas*, and the Rose-ringed Parakeet, *Psittacula krameri*), and several risk analyses have been tabled at meetings before these were submitted and approved by the Alien Species Risk Analysis Review Panel (e.g. coypu, *Myocastor coypus*, Mallard Duck (SANBI, unpublished) and Red-vented Bulbul, *Pycnonotus cafer*). It is envisaged that such documents will in future be routinely tabled at CAPE IAAWG before recommendations are submitted to the decision making body (DEFF).

The CAPE IAAWG has also not, as yet, been substantially involved in the discussion of the implementation and enforcement of the Regulations. There is an opportunity for the CAPE IAAWG to assist in trying to find the appropriate balance between incentive-based and penalty-based approaches. The proposed White Paper on Biological Invasions in South Africa will hopefully provide an opportunity for the CAPE IAAWG to influence the vision of how the control of alien animal populations is conducted in the future (Lukey & Hall 2020).

Success stories

The Mallard Strategy for South Africa was formulated by the working group's founder in 2008 and was subsequently adopted by Birdlife SA. Today this strategy guides the Mallard Duck project in the City of Cape Town and lays the foundation for similar projects as prescribed by national legislation (Mallard Ducks are listed as Category 2 in NEM: BA, though cf. SANBI unpublished).

The successful implementation of the Invasive Fish Project, including scientific credibility through a range of peer reviewed publications, culminated in two Water Research Commission reports that provided national guidelines for monitoring such projects and their ecological outcomes (Weyl et al. 2014; Marr et al. 2019).

The working group's discussions and interactions with stakeholders resulted in increased funding for invasive animal projects through the Natural Resources Management Programme of the DEFF (formerly Working for Water of the former Department of Environmental Affairs). To date four projects have been funded by DEFF: NRMP.

The working group was approached by the Wildlife and Environment Society of South Africa in 2009 to assist with a policy on earthworm cultivation using alien earthworms. In view of the scarcity of information on earthworm taxonomy and distributions in South Africa, the popularity of earthworm cultivation for compost, and accidental introductions through trade in soil and soil products, the group took a precautionary approach and declined to provide support to this enterprise. These discussions led to: (i) group members conducting an intensive sampling and mapping project of earthworm distributions in the Western Cape and KwaZulu-Natal; (ii) the formation of the Soil Ecosystem Research Group, a distributed network of South African researchers working on soil ecosystem and health; and (iii) the commissioning of a post-graduate research project on the threats, opportunities, costs and benefits of earthworm cultivation in South Africa. Unfortunately most of the research questions remain unanswered, and there is still a pressing need for foundational work to be conducted on alien earthworms in South Africa.

A vibrant, productive community of practice

It is important to note that many of the questions posed to the CAPE IAAWG needed to be answered through original research, for example by post-graduate students as part of their degree projects. In some cases the time taken to complete these projects is perceived as slowing down control operations, but it also ensures that the approaches that are finally used are fully tested and documented before they are implemented. This was a critical factor in the Invasive Fish Project, as the high output of scientific research projects confirmed that the Rondegat River rehabilitation project had been a conservation success, not a conservation disaster as some project critics feared it would be.

The diversity of perspectives in the working group provides those working in implementing agencies with the chance to solicit feedback on operational issues and discuss and consider bigger picture issues beyond their day-to-day concerns. In some cases, the feedback from working group members confirms that decision makers were already making appropriate and valued decisions, which is a very important, though hard to measure, component of building an effective community of practice. Pivotal to this was the development of trust between group members, and how this led to respect of the pressures and challenges of their different roles, facilitated by the person-to-person meetings of the group.

For researchers in the working group, the discussions provide valuable material for identifying research projects and anchoring them in real-world needs and priorities. When students working on invasive alien animal projects attend CAPE IAAWG meetings in person, they receive input, feedback and suggestions on the applied aspects of their work, as well as exposure to real world issues and insight into policy and management. Students also realise the importance of practical issues that need to be considered when research results are implemented. Their perspective on their work is broadened to include issues that many researchers do not become aware of until much later in their careers. Three post-graduate student research projects [Mallard Duck hybridisation with the native Yellow-billed Duck in Cape Town (Stephens et al. 2020); spread and adaptations of the guttural toad in the Western Cape (Vimercati et al. 2017a; 2017b; 2018; 2019); and the feasibility of marine eradications in South Africa with European shore crabs as a case study (Mabin et al. 2015; 2017; 2020)] have arisen from the working group. These projects were supervised by working group members and the students participated in the working group for the duration of their projects.

According to Dana et al. (2019), unsuccessful invasive alien animal control projects showed five characteristics: (i) the absence of funding during the necessary time to achieve the goals; (ii) the risk of reinvasion; (iii) an insufficient removal rate to achieve the specific objective; (iv) the absence of evidence reporting that the methodology applied is effective; and (v) the lack of adaptation of methodology to the expected population changes. The activities of the CAPE IAAWG helped to mitigate items (iii), (iv) and (v), but items (i) and (ii) are more challenging and lie partly beyond its remit. Biosecurity personnel working at a provincial and national level are increasingly involved in the working group, and this will ultimately help to address new invasions and the risk of re-invasion. Funding levels remain a serious challenge, as do the procedures required to release funds continuously and/or at short notice.

Support to implementers

The working group plays an important role in providing knowledge-based and logistical support to implementing agents (CapeNature, City of Cape Town, SANParks). For example, several of the control projects mentioned above (e.g. guttural toad control) were undertaken by private consultants, who, though skilled, do not always have an in-depth knowledge of the species being tackled at the commencement of a project. Contact with researchers and students who work on the target species provides a network of contacts that the implementers can draw on through the project life cycle. In turn, the information gathered by implementers has been valuable for later research on the species, which in turn improved outcomes. The CAPE IAAWG has also been involved with prioritisation of work programmes, helping implementers to identify the best approaches. Having the backing of an evidence-base is invaluable to decision makers. Personnel who have worked on this suite of projects are piloting the new techniques for the control of invasive alien populations of House Crow, guttural toads and Mallard Ducks. The City of Cape Town is planning to appoint a permanent professional officer to manage the House Crow and other invasive animal species projects, such as the guttural toad and mallard projects. This step aims to ensure the long-term sustainability of project activities, including monitoring invasion pathways and detecting new invasions.

Conclusion

The CAPE IAAWG has played a key role in facilitating the control of a variety of invasive alien animal species, and its members feel it has played a vital role in linking research, management, and policy in a manner accessible to both researchers and implementers. The CAPE IAAWG is not unique in South Africa, and there are a variety of working groups that link research, policy and management at national and regional levels (Davies et al. 2020). For example, the Marine Alien and Invasive Species Working Group, the KwaZulu-Natal Invasive Alien Species Forum, and the Eastern Cape Invasive Alien Species Forum have specific taxon or geographic mandates, and a variety of working groups focus on specific plant taxa such as invasive grasses, Australian trees and shrubs, and Cactaceae at national levels (Kaplan et al. 2017; Visser et al. 2017). The Fynbos Forum (Gelderblom & Wood 2018) is a GCFR community of practice with a much broader mandate that includes natural scientists, researchers, planners, land managers, landowners and stakeholders and 'meets annually to discuss the collaborative production of knowledge that underpins regional conservation efforts in the fynbos biome, South Africa' (https://fynbosforum. org. za/). Each working group is designed around its particular context and working arrangements.

While formal quantification of value of the CAPE IAAWG is presently difficult to achieve, several broadly applicable lessons are evident:

1. Funding delays can have serious and long-term consequences for projects that are time-bound; to some extent the delay between the decision to control and implementation of a project is normal as there are inevitable processes that need to be followed, e.g. to prepare funding applications, to register drugs or obtain ethical and public approval. However, excessive delays during implementation are often detrimental.
2. Stakeholder identification and engagement should be conducted as early as possible and should have a broad reach to ensure that projects are correctly designed and employ the most suitable methods. This is closely linked to point 1 because unnecessary delays during the project need to be avoided.
3. Ethical and animal welfare are important factors that should be taken seriously and collaboratively in the design phase of projects (see points 1 and 2 above).
4. Stability of working group membership both in terms of organisations and individuals is a key attribute of a successful working group. Each project needs successful drivers or champions that need support at difficult times. The model of a stable core with a larger rotating periphery, who participate as needed, has worked well for this working group.

A successful community of practice for inter-disciplinary work such as invasive species control and management must have benefits for all parties involved—government agencies, NGOs, university researchers and students. Specifically, this working group has played an important role in research becoming translational, in policy development and implementation and has improved the efficiency and effectiveness of invasive alien species control projects in the Cape Floral Region. If a working group is perceived as only serving or contributing to one institution's mandate it will quickly dissolve. Similarly, if there is substantial overlap with other working groups or forums, it will not be valued. The CAPE IAAWG fills an important gap between the generation and application of knowledge as shown by the continued participation and enthusiasm of members and support from their employer organisations to do so.

Based on the experiences as outlined in this paper, working groups like the CAPE IAAWG can help to lessen the gap between the production of science, the development of policy, and the implementation of adaptive management (learning and doing; Knight et al. 2008), and so have a vital positive impact on conservation outcomes. The accumulated insights will be useful for establishing, building, and maintaining more such communities of practice.

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Competing interests

The authors declare no competing interests.

Authors' contributions

All authors conceived the idea of the paper; all authors edited the manuscript and contributed to written sections; SJD wrote the article; NJVW, JM and SJD drew the figures.

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

References

Adelle, C., 2019, 'Creating knowledge democracy in South Africa: The role of communities of practice', *South African Journal of Science* 115, Art. #5888, 3 pages. https://doi.org/10.17159/sajs.2019/5888.

Allen, B.L., Allen, L.R., Ballard, G., Drouilly, M., Fleming, P.J.S., Hampton, J.O., Hayward, M.W., Kerley, G.I.H., Meek, P.D., Minniel, L., O'Riain, M.J., Parker, D.M. & Somers M.J., 2019, 'Animal welfare considerations for using large carnivores and guardian dogs as vertebrate biocontrol tools against other animals', *Biological Conservation* 232: 258–270. https://doi.org/10.1016/j.biocon.2019.02.019.

American Veterinary Medical Association, 2013, 'AVMA Guidelines for the euthanasia of animals', 2013 edn. Available at: https://www.avma.org/KB/Policies/Documents/euthanasia.pdf.

Bellingan, T.A., Hugo, S., Woodford, D.J., Gouws, J., Villet, M.H. & Weyl, O.L.F., 2019, 'Rapid recovery of macroinvertebrates in a South African stream treated with rotenone', *Hydrobiologia*, https://doi.org/10.1007/s10750-019-3885-z.

Benadé, P.C., Veldtman, R., Samways, M.J. & Roets, F., 2014, 'Rapid range expansion of the invasive wasp *Polistes dominula* (Hymenoptera: Vespidae: Polistinae) and first record of parasitoids on this species and the native *Polistes marginalis* in the Western Cape Province of South Africa', *African Entomology* 22: 220–225, https://doi.org/10.4001/003.022.0104.

Berruti, A., 1997, House crow, in J.A. Harrison, D.G. Allan, I.G. Underhill, M. Herremans, A.J. Tree, V. Parker & C.J. Brown, (eds.), *The Atlas of Southern African Birds Vol 2*, p. 108, *Bird Life South Africa, Johannesburg*.

Born, J., Linder, H.P. & Desmet, P., 2007, 'The Greater Cape Floristic Region', *Journal of Biogeography* 34: 147–162, https://doi.org/10.1111/j.1365-2699.2006 01595.x.

Botha, S.A., 1989, 'Feral Pigs in the Western Cape Province: Failure of a potentially invasive species', *South African Forestry Journal* 151: 17–25, https://doi.org/10.1080/00382167.1989.9630500

Caceres-Escobar, H., Kark, S., Atkinson, S.C., Possingham, H.P. & Davis, K.J., 2019, 'Integrating local knowledge to prioritise invasive species management', *People and Nature*, https://doi.org/10.1002/pan3.27

Carlton, J.T. & Cohen, A.N., 2003, 'Episodic global dispersal in shallow water marine organisms: the case history of the European shore crabs *Carcinus maenas* and *C. aestuarii*', *Journal of Biogeography* 30: 1809–1820, https://doi.org/10.1111/j.1365-2699.2003.00962.x.

Catalano, A.S., Lyons-White, J., Mills, M.M. & Knight, A.T., 2019, 'Learning from published project failures in conservation', *Biological Conservation* 238: 108223, https://doi.org/10.1016/j.biocon.2019.108223.

Colville, J.C., Potts, A.J., Bradshaw, P.L., Measey, G.J., Snijman, D., Picker, M.D., Procheş, S., Bowie, R.C.K. & Manning, J.C., 2014, 'Floristic and faunal Cape biochoria: do they exist?' in N. Allsopp, J.F. Colville, G.A. Verboom (eds.), *Fynbos: ecology, evolution, and conservation of a megadiverse region*, pp. 73–93, Oxford University Press, UK

Cooper, J.E., 1996, 'Health studies on the Indian House Crow (*Corvus splendens*)', *Avian Pathology* 25: 381–386.

Dana, E.D., García-de-Lomas, J., Verloove, F. & Vilà, M. 2019, 'Common deficiencies of actions for managing invasive alien species: a decision-support checklist', *NeoBiota* 48: 97–112, https://doi.org/10.3897/neobiota.48.35118.

Davies, S.J., Jordaan, M.S., Karsten, M., Terblanche, J.S., Turner, A.A., van Wilgen, N.J., Veldtman, R., Zengeya, T. & Measey, J., 2020, 'Experience and lessons from alien and invasive animal control projects carried out in South Africa', in B.W. van Wilgen, J. Measey, D.M. Richardson, J.R. Wilson, & T. Zengeya (eds.), *Biological Invasions in South Africa*, pp. 629–664, Springer, Berlin, https://doi.org/10.1007/978-3-030-32394-3_22.

De Moor, F.C. & Day, J.A., 2013, 'Aquatic biodiversity in the Mediterranean region of South Africa', *Hydrobiologia* 2013, https://doi.org/10.1007/s10750-013-1488-7.

De Moor, I.J. & Bruton, M.N., 1988, *Atlas of alien and translocated indigenous aquatic animals of southern Africa*. South African National Scientific Programmes Report 144, 310 pp.

De Villiers, A., 2006, '*Bufo gutturalis* Power, 1927. Introduced population', *African Herp News* 40: 28–30.

Dean, W.R.J. 2000, 'Alien birds in southern Africa: what factors determine success?' *South African Journal of Science* 96: 9–14

Ellender, B.R., Wasserman, R.J., Chakona, A., Skelton, P.H. & Weyl, O.L.F., 2017, 'A review of the biology and status of Cape Fold Ecoregion freshwater fishes', *Aquatic Conservation*, https://doi.org/10.1002/aqc.2730.

Ellender, B.R., Woodford, D.J., Weyl, O.L.F. & Cowx, I.G., 2014, 'Managing conflicts arising from fisheries enhancements based on non-native fishes in southern Africa', *Journal of Fish Biology* 85: 1890–1906, https://doi.org/10.1111/jfb.12512.

Enquist, C.A., Jackson, S.T., Garfin, G.M., Davis, F.W., Gerber, L.R., Littell, J.A., Tank, J.L., Terando, A.J., Wall, T.U., Halpern, B., Hiers, J.K., Morelli, T.L., McNie, E., Stephenson, N.L., Williamson, M.A., Woodhouse, C.A., Yung, L., Brunson, M.W., Hall, K.R., Hallet, L.M., Lawson, D.M., Moritz, M.A., Nydick, K., Pairis, A., Ray, A.J., Regan, C., Safford, H.D., Schwartz, M.W. & Shaw, M.R., 2017, 'Foundations of translational ecology', *Frontiers in Ecology and the Environment* 15: 541–550, https://doi.org/10.1002/fee.1733.

Esler, K.J., Prozesky, H., Sharma, G.P. & McGeoch, M., 2010, 'How wide is the "knowing–doing" gap in invasion biology?', *Biological Invasions* 12: 4065–4075, https://doi.org/10.1007/s10530-010-9812-x.

Essl, F., Dullinger, S., Genovesi, P., Hulme, P.E., Jeschke, J.M., Katsanevakis, S., Kühn, I., Lenzner, B., Pauchard, A., Pyšek, P., Rabitsch, W., Richardson, D.M., Seebens, H., Van Kleunen, M., Van der Putten, W.H., Vilà M. & Bacher S., 2019, 'A conceptual framework for range-expanding species that track human-induced environmental change', *BioScience* biz101, https://doi.org/10.1093/biosci/biz101.

Evans, T., Kumschick, S. & Blackburn, T.M., 2016, 'Application of the Environmental Impact Classification for Alien Taxa (EICAT) to a global assessment of alien bird impacts', *Diversity and Distributions* 22: 919–931, https://doi.org/10.1111/ddi.12464.

Finlayson, B., Schnick, R., Skaar, D., Anderson, J., DeMong, L., Duffield, D., Horton, W. & Steinkjer, J., 2010, *Planning and standard operating procedures for the use of rotenone in fish management*, American Fisheries Society, Bethesda, Maryland

Fowler, A.C., Eadie, J.M. & Engilis, A., 2009, 'Identification of endangered Hawaiian ducks (*Anas wyvilliana*), introduced North American mallards (*A. platyrhynchos*) and their hybrids using multilocus genotypes', *Conservation Genetics* 10: 1747–1758, https://doi.org/10.1007/s10592-008-9778-8.

Foxcroft, L.C., van Wilgen, B.W., Abrahams, B., Esler, K.J. & Wannenburgh, A., 2020, 'Knowing–doing continuum or knowing–doing gap? Information flow between researchers and managers of biological invasions in South Africa', in B.W. van Wilgen, J. Measey, D.M. Richardson, J.R. Wilson, & T. Zengeya (eds.), *Biological Invasions in South Africa*, pp. 831–854, Springer, Berlin, https://doi.org/10.1007/978-3-030-32394-3_28.

Fraser, D. & MacRae, A.M., 2011, 'Four types of activities that affect animals: implications for animal welfare science and animal ethics philosophy', *Animal Welfare* 20: 581–590.

Gaertner, M., Larson, B.M., Irlich, U.M., Holmes, P.M., Stafford, L., van Wilgen, B.W. & Richardson, D.M., 2016, 'Managing invasive species in cities: A framework from Cape Town, South Africa', *Landscape and Urban Planning* 151: 1–9.

Gelderblom, C. & Wood, J. 2018, *The Fynbos Forum: Its Impacts and history*. The Fynbos Forum, Cape Town. 226 pp. ISBN: 978-0-620-80362-5

Groom, Q., Desmet, P., Reyserhove, L., Adriaens, T., Oldoni, D., Vanderhoeven, S., Baskauf, S.J., Chapman, A., McGeoch, M., Walls, R., Wieczorek, J., Wilson, J.R.U., Zermoglio, P.F.F. & Simpson, A., 2019, 'Improving Darwin Core for research and management of alien species', *Biodiversity Information Science and Standards* 3, e38084.

Hagen, B.L. & Kumschick, S., 2018, 'The relevance of using various scoring schemes revealed by an impact assessment of feral mammals', *NeoBiota* 38: 37–75. https://doi.org/10.3897/neobiota.38.23509.

Hawkins, C.L., Bacher, S., Essl, F., Hulme, P.E., Jeschke, J.M., Kühn, I., Kumschick, S., Nentwig, W., Pergl, J., Pyšek, P., Rabitsch, W., Richardson, D.M., Vilà, M., Wilson, J.R.U., Genovesi, P. & Blackburn, T.M., 2015, 'Framework and guidelines for implementing the proposed IUCN Environmental Impact Classification for Alien Taxa (EICAT)', *Diversity and Distributions* 21: 1360–1363.

Hofmeyr, M.D. & Baard, E.H.W. 2018, '*Psammobates geometricus*', The IUCN Red List of Threatened Species: e. T18398A111553007 https://doi.org/10.2305/IUCN.UK.2018-2.RLTS.T18398A111553007.en. Downloaded on 8 November 2019

Impson, N.D., van Wilgen, B.W. & Weyl, O.L.F., 2013, 'Co-ordinated approaches to rehabilitating a river ecosystem invaded by alien plants and fish', *South African Journal of Science* 109: 3–6, https://doi.org/10.1590/sajs.2013/a0041.

Jackson, L., Wilson, J. & Kumschick, S., 2015, 'The prioritisation of invasive alien animal projects by the National Invasive Animal Forum: Recommendations'. p. 16, Department of Environmental Affairs, South Africa.

Janion-Scheepers, C., Measey, J., Braschler, B., Chown, S.L., Coetzee, L., Colville, J.F., Dames, J., Davies, A.B., Davies, S.J., Davis, A., Dippenaar-Schoeman, A.S., Duffy, G.A., Fourie, D., Griffiths, C., Haddad, C.R., Hamer, M., Herbert, D., Hugo-Coetzee, E.A., Jacobs, A., Jacobs, K., Jansen van Rensburg, C., Lamani, S., Lotz, L.N., Louw, S.v.d.M., Lyle, R., Malan, A.P., Marais, M., Neethling, J.-A., Nxele, T., Plisko, D., Prendini, L., Rink, A.N., Swart, A., Theron, P., Truter, M., Ueckermann, E., Uys, V.M., Villet, M.H., Willows-Munro, S. & Wilson, J.R., 2016, 'Soil biota in a megadiverse country: current knowledge and future research directions in South Africa'. *Pedobiologia* 59: 129–174, https://doi.org/10.1016/j.pedobi.2016.03.004.

Joska, M.A. & Branch, G.M. 1986, 'The European shore crab – another invader?', *African Wildlife* 40: 63–64.

Kaplan, H., Wilson, J.R.U., Klein, H., Henderson, L., Zimmermann, H.G., Manyama, P., Ivey, P., Richardson, D.M. &

Novoa, A., 2017, 'A proposed national strategic framework for the management of Cactaceae in South Africa', *Bothalia – African Biodiversity and Conservation* 47, a2149. https://doi.org/10.4102/abc.v47i2.2149.

Knight, A.T., Cowling, R.M., Rouget, M., Balmford, A., Lombard, A.T. & Campbell, B.M., 2008, 'Knowing but not doing: Selecting priority conservation areas and the research–implementation gap', *Conservation Biology* 22: 610–617, https://doi.org/10.1111/j.1523-1739.2008.00914.x.

Kumschick, S., Foxcroft, L.C. & Wilson, J.R., 2020, 'Analysing the risks posed by biological invasions to South Africa', in B.W. van Wilgen, J. Measey, D.M. Richardson, J.R. Wilson, & T. Zengeya (eds.), *Biological Invasions in South Africa*, pp. 573–596, Springer, Berlin, https://doi.org/10.1007/978-3-030-32394-3_20.

Kumschick, S., Vimercati, G., de Villiers, F.A., Mokhatla, M.M., Davies, S.J., Thorp, C.J., Rebelo, A.D. & Measey, G.J., 2017, 'Impact assessment with different scoring tools: How well do alien amphibian assessments match?', *NeoBiota* 33: 53–66, https://doi.org/10.3897/neobiota.33.10736.

Kumschick, S., Wilson, J.R. & Foxcroft, L.C., 2018, 'Framework and guidelines for conducting risk analyses for alien species', Preprints, https://doi.org/10.20944/preprints201811.200551.v201811.

Leprieur, F., Beauchard, O., Blanchet, S., Oberdorff, T. & Brosse, S., 2008, 'Fish invasions in the world's river systems: when natural processes are blurred by human activities', *PLoS Biology* 6, e28, https://doi.org/10.1371/journal.pbio.0060028.

Lester, P.J. & Beggs, J.R., 2019, 'Invasion success and management strategies for social *Vespula* wasps', *Annual Review of Entomology* 64: 51–71, https://doi.org/10.1146/annurev-ento-011118-111812.

Liversidge, R. 1985, 'Alien bird species introduced into southern Africa', in L.J. Bunning (ed.), Birds and Man Symposium, Johannesburg 1983, Witwatersrand Bird Club, Johannesburg

Long, J.L., 1981, *Introduced birds of the world: the worldwide history, distribution and influence of birds introduced to new environments*, London: David and Charles.

Lukey, P. & Hall, J., 2020, 'Biological invasion policy and legislation development and implementation in South Africa', in B.W. van Wilgen, J. Measey, D.M. Richardson, J.R. Wilson, & T. Zengeya (eds.), *Biological Invasions in South Africa*, pp. 515–552, Springer, Berlin, https://doi.org/10.1007/978-3-030-32394-3_18.

Mabin, C.A., Wilson, J.R.U. & Robinson, T.B., 2015, 'The Chilean black urchin, *Tetrapygus niger* (Molina, 1782) in South Africa: gone but not forgotten', *BioInvasions Records*, 4: 261–264.

Mabin, C.A., Wilson, J.R.U., Le Roux, J.J. & Robinson, T.B., 2017, 'Reassessing the invasion of South African waters by the European shore-crab *Carcinus maenas*', *African Journal of Marine Science* 39: 259–267, https://doi.org/10.2989/1814232X.2017.1363818.

Mabin, C.A., Wilson, J.R.U., Le Roux, J.J., Majiedt, P. & Robinson, T.B., 2020, 'The first management of a marine invader in Africa: The importance of trials prior to setting long-term management goals', *Journal of Environmental Management* 261: 110213, https://doi.org/10.1016/j.jenvman.2020.110213.

Marr, S.M., Bellingan, T., Dalu, T., Impson, D., Jordaan, M., Slabbert, E., Gouws, G., Hugo, S., Mofu, L., Khosa, D & Weyl, O., 2019, 'Rotenone policy support and capacity development. Part 1: Impact and recovery of biota in one river and two dams following alien fish removals using rotenone', Water Research Commission Report, TT 780/1/18.

Marr, S.M., Impson, N.D. & Tweddle, D., 2012, 'An assessment of a proposal to eradicate non-native fish from priority rivers in the Cape Floristic Region, South Africa', *African Journal of Aquatic Science* 37: 131–142, https://doi.org/10.2989/16085914.2012.666654.

McIlroy, J.C. & Gifford, E.J., 1997, 'The Judas pig technique: a method that could enhance control programmes against feral pigs, *Sus scrofa*', *Wildlife Research* 2: 483–491.

Measey, J., Annecke, W., Davies, S., Dorse, C., Stafford, L., Tolley, K. & Turner, A., 2014, 'Cape collaborations for amphibian solutions', *FrogLog* 109: 46–47.

Measey, J., Davies, S.J., Vimercati, G., Rebelo, A., Schmidt, W. & Turner, A., 2017, 'Invasive amphibians in southern Africa: A review of invasion pathways', *Bothalia – African Biodiversity and Conservation* 47, a2117. https://doi.org/10.4102/abc.v47i2.2117.

Measey, J., Hui, C. & Somers, M. 2020, 'Terrestrial vertebrate invasions in South Africa', in B.W. van Wilgen, J. Measey, D.M. Richardson, J.R. Wilson, & T. Zengeya (eds.), *Biological Invasions in South Africa*, pp. 787–830, Springer, Berlin, https://doi.org/10.1007/978-3-030-32394-3_27.

National Environmental Management Act (Act No. 107 of 1998), 1998, *Government Gazette of South Africa* 401(19519), 1-72. Available at: https://www.environment.gov.za/sites/default/files/legislations/nema_amendment_act107_0.pdf.

National Environmental Management: Biodiversity Act (Act No. 10 of 2004), 2004, *Government Gazette of South Africa* 467(26436), 2-84. Available at: https://www.environment.gov.za/sites/default/files/legislations/nema_amendment_act10_0.pdf.

National Environmental Management: Biodiversity Act, Alien and Invasive Species Regulations, 2014, *Government Gazette of South Africa* 590(37885), 1–32. Available at: https://www.environment.gov.za/sites/default/files/legislations/nemba10of2004_alienandinvasive_speciesregulations_0.pdf.

National Environmental Management: Biodiversity Act, Alien and Invasive Species Lists 2016, *Government Gazette of South Africa* 613(40166), 31-104. Available at: https://www.environment.gov.za/sites/default/files/gazetted_notices/nemba10of2004_alienandinvasive_specieslists2016_0.pdf

Novoa, A., Dehnen-Schmutz, K., Fried, J. & Vimercati, G., 2017, 'Does public awareness increase support for invasive species management? Promising evidence across taxa and landscape types', *Biological invasions* 19: 3691–3705, https://doi.org/10.1007/s10530-017-1592-0.

Novoa, A., Shackleton, R., Canavan, S., Cybèle, C., Davies, S.J., Dehnen-Schmutz, K., Fried, J., Gaertner, M., Geerts, S., Griffiths, C.L., Kaplan, H., Kumschick, S., Le Maitre, D.C., Measey, G.J., Nunes, A.L., Richardson, D.M., Robinson, T.B., Touza, J. & Wilson, J.R.U., 2018, 'A framework for engaging stakeholders on the management of alien species', *Journal of Environmental Management* 205: 286–297, https://doi.org/10.1016/j.jenvman.2017.09.059.

Nyári, A., Ryall, C. & Peterson, P. 2006, 'Global invasive potential of the house crow *Corvus splendens* based on ecological niche modelling', *Journal of Avian Biology* 37: 306–311.

Nxele, T.C., Lamani, S., Measey, G.J., Armstrong, A.J., Plisko, J.D., Willows-Munro, S., Janion-Scheepers, C. & Wilson, J.R.U., 2015, 'Studying earthworms (Annelida: Oligochaeta) in South Africa', *African Invertebrates* 56: 779–806, https://doi.org/10.5733/afin.056.0319.

Oatley, T.B., 1973, 'Indian house crow – first SA sightings', *Bokmakierie* 25: 41–42.

O'Hare, J.R., Eisemann, J.D., Fagerstone, K.A., Koch, L.L. & Seamans, T.W., 2007, 'Use of alpha-chloralose by USDA Wildlife Services to immobilize birds', *USDA National Wildlife Research Center - Staff Publications* 769: 1–11.

Owen, M., Callaghan, D. & Kirby, J., 2006, *Guidelines on avoidance of introductions of non-native waterbird species*, Bonn: UNEP/AEWA Secretariat.

Plisko, J.D. & Nxele, T.C., 2015, An annotated key separating foreign earthworm species from the indigenous South African taxa (Oligochaeta: Acanthodrilidae, Eudrilidae, Glossoscolecidae, Lumbricidae, Megascolecidae, Microchaetidae, Ocnerodrilidae and Tritogeniidae), *African Invertebrates* 56: 663–708.

Plisko, J.D., 2001, 'Notes on the occurrence of the introduced earthworm *Pontoscolex corethrurus* (Müller, 1857) in South Africa (Oligochaeta: Glossoscolecidae)', *African Invertebrates* 42: 323–334.

R Core Team, 2018, 'R: A language and environment for statistical computing', R Foundation for Statistical Computing, Vienna, Austria, URL https://www.R-project.org/.

Rhymer, J.M., Williams, M.J. & Braun, M.J., 1994, 'Mitochondrial analysis of gene flow between New Zealand mallards (*Anas platyrhynchos*) and grey ducks (*A. superciliosa*)', *The Auk* 111, 970–978, https://doi.org/10.2307/4088829.

Ryall, C., 2016, 'Further records and updates of range expansion in House Crow *Corvus splendens*', *Bulletin of the British Ornithologists' Club* 136: 39–45.

Robinson, T.B., Peters, K. & Brooker, B., 2020, 'Coastal invasions: The South African context', in B.W. van Wilgen, J. Measey, D.M. Richardson, J.R. Wilson, & T. Zengeya (eds.), *Biological Invasions in South Africa*, pp. 229–248, Springer, Berlin, https://doi.org/10.1007/978-3-030-32394-3_9.

SANBI, 2019, 'Risk analysis of *Vespula germanica* (Fabricius, 1973) for South Africa', Approved by the South African Alien Species Risk Analysis Review Panel on 30 April 2019, 19 pages.

SANBI, unpublished, 'Risk analysis of *Anas platyrhynchos* (Linnaeus, 1758) for South Africa as per the risk analysis of alien taxa framework v1.1', approved by the South African Alien Species Risk Analysis Review Panel on 19 March 2020, pp 23. http://dx.doi.org/10.5281/zenodo.3716165.

Schlesinger, W.H., 2010, 'Translational ecology', *Science* 329: 609–609, https://doi.org/10.1126/science.1195624.

Shackleton, R.T., Novoa, A., Shackleton, C.M. & Kull, C.A., 2020, 'The social dimensions of biological invasions in South Africa', in B.W. van Wilgen, J. Measey, D.M. Richardson, J.R. Wilson, & T. Zengeya (eds.), *Biological Invasions in South Africa*, pp. 701–732, Springer, Berlin, https://doi.org/10.1007/978-3-030-32394-3_24.

Shelton, J.M., Samways, M.J. & Day, J.A., 2015, 'Predatory impact of non-native rainbow trout on endemic fish populations in headwater streams of the Cape Floristic Region of South Africa', *Biological Invasions* 37: 365–379, https://doi.org/10.1007/s10530-014-0735-9.

Skead, C.J., Boshoff, A., Kerley, G.I.H. & Lloyd, P., 2011,' Introduced (non-indigenous) species: A growing threat to biodiversity', in C.J. Skead, A. Boshoff, G.I.H. Kerley & P. Lloyd (eds.), Volume 1: *Historical Incidence of the Larger Land Mammals in the Broader Northern and Western Cape*, pp. 468–487, Centre for African Conservation Ecology, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa

South African Bird Atlas Project 2, 2019, 'Duck, Mallard (*Anas platyrhynchos*)', Available from: http://sabap2.adu.org.za/species/1016#pgcontent.

Spear, D. & Chown, S.L., 2009, 'Non-indigenous ungulates as a threat to biodiversity', *Journal of Zoology* 279, 1–17, https://doi.org/10.1111/j.1469-7998.2009.00604.x.

Stafford, L., 2010, 'Mallard Strategy for South Africa', Available online: http://www.wingshooters.co.za/pdf/National-MallardStrategy-May10.pdf.

Stephens, K., Measey, J., Reynolds, C. & Le Roux, J.J., 2020, 'Occurrence and extent of hybridization between the invasive Mallard Duck and native Yellow-billed Duck in South Africa', *Biological Invasions* 22, 693–707, https://doi.org/10.1007/s10530-019-02122-6.

Telford, N., Channing, A. & Measey, J., 2019, 'Origin of invasive populations of the guttural toad *Sclerophrys gutturalis*', *Herpetological Conservation & Biology* 14: 380–392.

Tweddle, D., Bills, R., Swartz, E., Coetzer, W., Da Costa, L., Engelbrecht, J., Cambray, J., Marshall, B., Impson, D., Skelton, P., Darwall, W. & Smith, K., 2009, 'The status and distribution of freshwater fishes', in W. Darwall, K. Smith, D. Tweddle & P. Skelton (eds.), *The Status and Distribution of Freshwater Biodiversity in Southern Africa*. IUCN Red List of Threatened Species, Regional Assessment, pp. 21–37.

Van Wilgen, B.W. & Wilson, J.R. (eds.), 2018, *The status of biological invasions and their management in South Africa in 2017*, South African National Biodiversity Institute, Kirstenbosch and DST-NRF Centre of Excellence for Invasion Biology, Stellenbosch, ISBN: 978-1-928224-18-1. 420 pp.

Van Zyl, C., Addison, P. & Veldtman, R., 2018, 'The invasive Vespidae in South Africa: potential management strategies and current status', *African Entomology* 26: 267–285, https://doi.org/10.4001/003.026.0267.

Veldtman, R., Addison, P. & Tribe, G.D., 2012, 'Current status and potential future impact of invasive vespid wasps (*Vespula germanica* and *Polistes dominulus*) in South Africa', *IOBC/wprs Bulletin* 75, 217–21.

Vimercati, G., Davies, S.J., Hui, C. & Measey, G.J., 2017a, 'Does restricted access limit management of invasive urban frogs?', *Biological Invasions* https://doi.org/10.1007/s10530-017-1599-6.

Vimercati, G., Hui, C., Davies, S.J. & Measey, G.J. 2017b, 'Integrating age structured and landscape resistance models to disentangle invasion dynamics of a pond-breeding anuran', *Ecological Modelling* 356, 104–116. https://doi.org/10.1016/j.ecolmodel.2017.03.017

Vimercati, G., Davies, S.J. & Measey, J., 2018, 'Rapid adaptive response to a mediterranean environment reduces phenotypic mismatch in a recent amphibian invader', *Journal of Experimental Biology* https://doi.org/10.1242/jeb.174797.

Vimercati, G., Davies, S.J. & Measey, J., 2019, 'Invasive toads adopt marked capital breeding when introduced to a cooler, more seasonal environment', *Biological Journal of the Linnean Society* https://doi.org/10.1093/biolinnean/blz119.

Visser, V., Wilson, J.R.U., Canavan, K., Canavan, S., Fish, L., Le Maitre, D., Nänni, I., Mashau, C., O'Connor, T.G., Ivey, P., Kumschick, S. & Richardson, D.M., 2017, 'Grasses as invasive plants in South Africa revisited: patterns, pathways and management', *Bothalia – African Biodiversity and Conservation* 47, a2169. https://doi.org/10.4102/abc.v47i2.2169.

Weyl, O.L.F., Finlayson, B., Impson, N.D., Woodford, D.J. & Steinkjer, J., 2014, 'Threatened endemic fishes in South Africa's Cape Floristic Region: a new beginning for the Rondegat River', *Fisheries* 39: 270–279, https://doi.org/10.1080/03632415.2014.914924.

Weyl, O.L.F., Ellender, B.R., Woodford, D.J. & Jordaan, M.S., 2013, 'Fish distributions in the Rondegat River, Cape Floristic Region, South Africa, and the immediate impact of rotenone treatment in an invaded reach', *African Journal of Aquatic Science* 28: 201–209, https://doi.org/10.2989/16085914.2012.753401.

Weyl, O.L.F., Finlayson, B., Impson, N.D., Woodford, D.J. & Steinkjer, J., 2014, 'Threatened endemic fishes in South Africa's Cape Floristic Region: a new beginning for the Rondegat River', *Fisheries* 39: 270–279, https://doi.org/10.1080/03632415.2014.914924.

Weyl, O.L.F., Ellender, B.R., Wassermann, R.J., Truter, M., Dalu, T., Zengeya, T.A. & Smit, N.J., 2020, 'Alien freshwater fauna in South Africa', in B.W. van Wilgen, J. Measey, D.M. Richardson, J.R. Wilson, & T. Zengeya (eds.), *Biological Invasions in South Africa*, pp. 153–184, Springer, Berlin, https://doi.org/10.1007/978-3-030-32394-3_6.

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L.D., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T.L., Miller, E., Bache, S.M., Müller, K., Ooms, J., Robinson, D., Seidel, D.P., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K. & Yutani, H., 2019, 'Welcome to the tidyverse', *Journal of Open Source Software* 4, 1686, https://doi.org/10.21105/joss.01686.

Wilson J.R., Panetta F.D. & Lindgren C., 2017, *Detecting and responding to alien plant incursions*, Cambridge University Press, UK, 265 pp., https://doi.org/10.1017/CBO9781316155318.

Wilson, J.R.U., Faulkner, K.T., Rahlao, S.J., Richardson, D.M., Zengeya, T.A. & van Wilgen, B.W., 2018, 'Indicators for monitoring biological invasions at a national level', *Journal of Applied Ecology* 55: 2612–2620, https://doi.org/10.1111/1365-2664. 13251.

Wilson, J.R.U., Ivey, P., Manyama, P. & Nänni, I., 2013, 'A new national unit for invasive species detection, assessment and eradication planning', *South African Journal of Science* 109, Art. #0111, 13 pages, http://dx.doi.org/10.1590/sajs.2013/20120111.

Woodford, D.J., Impson, N.D., Day, J.A. & Bills, I.R., 2005, 'The predatory impact of invasive alien Smallmouth Bass, *Micropterus dolomieu* (Teleostei: Centrarchidae), on indigenous fishes in a Cape Floristic Kingdom mountain stream', *African Journal of Aquatic Science* 30: 167–173, https://doi.org/10.2989/16085910509503852.

Yeld, J., 2010, 'City declares war on house crows . . . again. Cash awaited for project to eliminate "pests"', *Cape Argus* 2010 August 19.

Zengeya, T.A. & Wilson, J.R. (Eds.), 2020, 'The status of biological invasions and their management in South Africa in 2019'. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch, https://doi.org/10.5281/zenodo.3947613

Supplementary material

Appendix 1: Goals and objectives of the CAPE invasive species strategy

Goal 1: Invasive Alien Species in the Greater CFR managed within appropriate policy and legislative frameworks.	**Objective:** Ensure that the management of invasive species in the Greater CFR is consistent with the relevant legislation.
Goal 2: Actions of all role-players harmonised through strategic planning.	**Objective:** Provide a framework for a coherent regional action plan through the prioritisation of invasive species management at appropriate scales.
Goal 3: Appropriate awareness raising, institutional arrangements and capacity building implemented.	**Objective:** Raise awareness and increase buy-in to combat the invasive species problem; improve institutional arrangements for invasive species management in the Greater CFR; build institutional capacity in the Greater CFR to address invasive species problems and improve invasive species management.
Goal 4: Introduction and establishment of new invasive species prevented through early detection and rapid response.	**Objective:** Prevent the intentional and/or unintentional introduction of invasive species and prevent new invasive species establishing or spreading through early detection and rapid
Goal 5: Impact of existing invasive species reduced through the implementation of integrated control measures.	**Objective:** Give effect to the obligations on landowners i.t.o. NEMBA Chapter 5; incorporate invasive species management into all land use decisions.
Goal 6: Adaptive management is informed by research, monitoring and evaluation.	**Objective:** Implement invasive species monitoring, evaluation and research programmes to enhance invasive species management.

Appendix 2: CAPE Invasive Alien Animal Working Group Terms of Reference (2018)

1. Preamble

A Memorandum of Understanding (MoU) was entered into in September 2001 with government departments, municipalities, statutory bodies and accredited non-governmental organisations that will carry out the vision of C. A. P. E. This TOR is entered into under the CAPE MOU and establishes the C. A. P. E. Invasive Animal Working Group (C. A. P. E. IAA WG), the Terms of Reference (TOR) of which is elaborated here. Provision is also made here for the future of this working group after the expiry of the CAPE project as it fulfills a function that is not time bound.

2. Purpose

The C. A. P. E. IAA WG was established to enhance cooperation and synergy amongst stakeholders and implementing agents through strategic planning, monitoring progress and developing case studies to inform best practice of invasive alien animal species (IAAS) management in the Greater CFR. Until the end of 2020 the scope of the WG includes the Greater CFR but will expand to cover the Western Cape Province thereafter. The C. A. P. E. IAA WG will endeavor to monitor the impact of IAS control operations based on information provided by implementing agents.

The business of the C. A. P. E IAA WG includes the coordination of activities covering the following areas as they relate to IAAS and IAAS management:

- Knowledge sharing;
- Research, monitoring and evaluation;
- Awareness and capacity-building;
- Information dissemination;
- Prevention;
- Early detection and rapid response;
- Policy and best practice;
- Funding;
- Prioritizing projects.

The C. A. P. E IAA WG provides a forum for the exchange of views on the means of implementing best practice in the field of IAAS management for the purpose of facilitating and improving IAAS management.

Specific collaborative activities shall be carried out in accordance with the C. A. P. E. MOU and relevant legislation.

The C. A. P. E IAA WG is not intended to replace, inhibit or duplicate activities of other organizations or agreements.

3. Objectives

The C. A. P. E. IAA WG aims to achieve the following objectives:

- Share expert IAAS knowledge amongst institutions to improve implementation and alignment;
- Mobilise and/or lobby support for IAAS management programmes;
- Identify and prioritise research requirements and priority management interventions;
- Communicate research outcomes for implementation;
- Monitor implementation of IA strategic actions;
- Facilitate development and standardization of IAAS Policy;
- Harmonize policy towards dealing with IAAS with other provinces and working groups through relevant forums.

4. Structure

The C. A. P. E IAA WG consists of stakeholder representatives from appropriate tertiary, conservation, institutions and organs of state.

Membership of the C. A. P. E IAA WG will be issued to appropriate stakeholders who must send and appoint representatives for each meeting or activity of the WG.

There shall be a chairperson elected every two years by the members.

The election shall take place via an electronic ballot. Members will be given ten working days to cast their votes. After his period the person receiving the greatest number of votes will appointed chairperson.

The importance of consultation with other agencies and organisations is recognised. Representatives from specific academic institutions and conservation agencies may be invited to participate in technical discussions but will not become members of the C. A. P. E IAA WG. They may, however, become members of a working group established for a specific area of expertise or project.

The participating institutions commit to implementing decisions of the C. A. P. E IAA WG.

Meetings of the CAPE IAA WG

The chairperson shall be responsible for organising meetings of the IAA WG and appointing meeting chairs when required.

The IAA WG shall endeavor to meet at least twice a year.

Minutes shall be prepared and provided to C. A. P. E IAA WG members within two weeks following the meeting. Secretarial support for these meetings is the responsibility of the chairperson.

5. Exchange of Information

Information shall be exchanged during IAA WG meetings by means of discussions, presentations, documentation attached to the minutes, or formalised and focused workshops to address particular issues of concern. The participants are responsible for disseminating information to their organisations and local stakeholders.

6. Status

This TOR constitutes guiding principles to coordinate C. A. P. E IAA WG activities between the participants. Any collaborative activities identified for investigation by the C. A. P. E IAA WG will be pursued in accordance with the terms and provisions of the C. A. P. E. MOU.

7. Effective Date.

This updated and amended TOR for the C. A. P. E IAA WG becomes effective on 1st of June 2018 and remains in effect until April 2022, unless terminated or extended by the by mutual written consent of the C. A. P. E IAA WG participants to accommodate the termination of the CAPE MOU and new priorities that may arise.

8. Definitions and Acronyms.

Definitions

Participants: Individuals representing their institutions in sharing and participating in the activities of the WG.

Partnership: A formal agreement between two or more parties that have agreed to work together in the pursuit of common goals.

Implementing agents: Government institutions implementing Invasive Animal projects in the Greater CFR.

Acronyms and abbreviations

C. A. P. E. IAA WG . . . CAPE Invasive Animal Working Group
C. A. P. E. . . . . Cape Action Plan for People and the Environment
CFR . . . . Cape Floristic Region
CIB . . . . DSI-NRF/Centre of Excellence Centre for Invasion Biology
Greater CFR . . . . Cape Floristic Region including the rest of the Western Cape Province
IAAS . . . . Invasive Animal Species
IAS . . . . Invasive Alien Species
MOU . . . . Memorandum of Understanding
SANBI . . . . South African National Biodiversity Institute
TOR . . . . Terms of Reference
WG . . . . Working Group

PARTICIPANTS

Institution	Signature	Date
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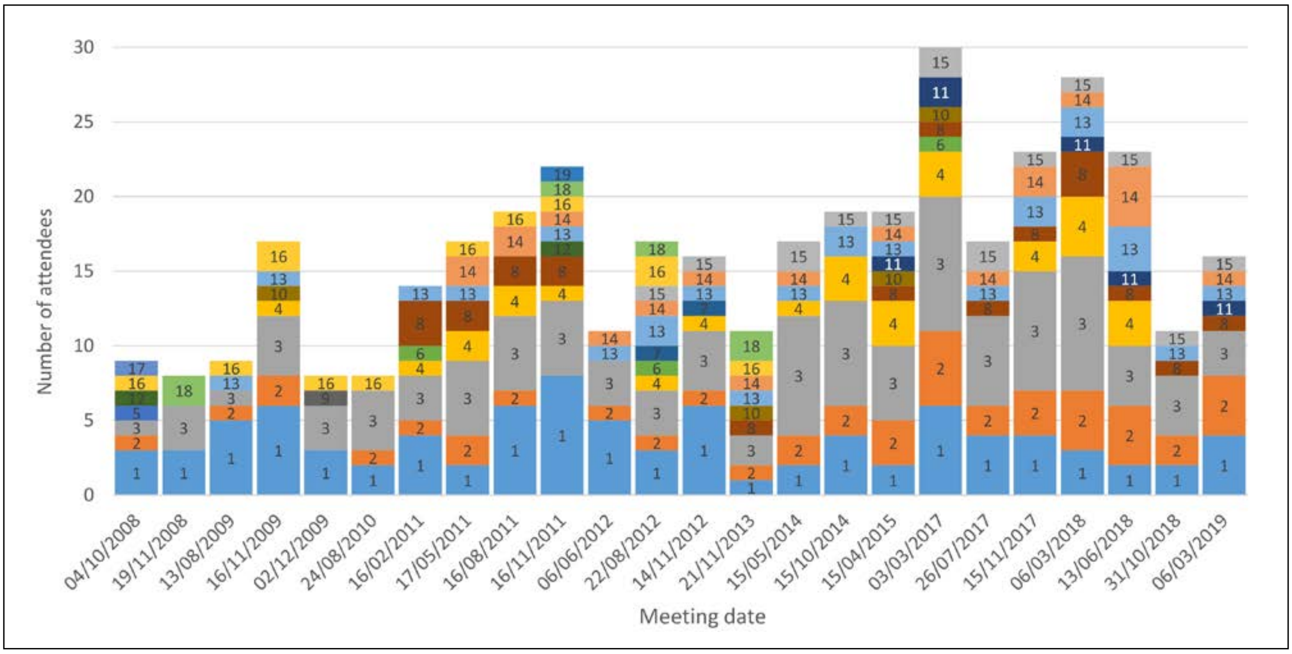
Appendix 3: Institutional attendance at CAPE IAAWG meetings.



Institution codes: 1. CapeNature; 2. Centre for Invasion Biology; 3. City of Cape Town; 4. Dept. Environment Affairs (now Dept. Environment, Forestry and Fisheries); 5. Department of Agriculture; 6. Eastern Cape Parks & Tourism Agency; 7. Intaka Island; 8. NCC Environmental Services; 9. Nelson Mandela University; 10. Private; 11. Robben Island Museum; 12. South African Institute for Aquatic Biodiversity; 13. South African National Biodiversity Institute; 14. South African National Parks; 15. SPCA; 16. University of Cape Town; 17. University of the Western Cape; 18. Visiting Scientist; 19. Wildlife and Environment Society of South Africa.

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Captive large predators killing vultures: exposing captive facilities as an additional source of mortality to highly threatened birds

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Background and objective: African vultures are under pressure from various, well-known anthropogenic threats. Here we describe and aim to highlight a little-known source of mortality to two Critically Endangered vulture species (*Gyps africanus* and *Necrosyrtes monachus*), as well as the Endangered Cape Vulture (*Gyps coprophores*) in southern Africa – that of captive big cats killing vultures that land in their enclosures to feed on food scraps or faeces or to bathe in drinking water.

Methods: Personal observations, reports from public, interviews with current and former staff from predator parks and lion hunting ranches.

Discussion: While the spatial and numerical extent of this mortality has not yet been quantified, if it is found to be widespread then failure to address it may present a risk to the regions' vulture populations.

Conclusion: We encourage captive breeding facilities and regulatory authorities to take appropriate action to prevent free-roaming vultures from coming into contact with captive big cats, and we highlight the need for further research to determine the spatial extent and magnitude of this threat to African vultures.

Keywords: captive big cats, *Gyps africanus*, Hooded Vulture, *Necrosyrtes monachus*, *Panthera*, threat, vulture, White-backed Vulture.

Introduction

Africa's vultures are facing an extinction crisis (Ogada et al. 2016a) similar to that experienced by Asia's vultures (Oaks et al. 2004), and both result from anthropogenic factors. The main anthropogenic threats to African vultures are deliberate poisoning by poachers, secondary poisoning, the illegal trade in vulture body parts for belief-based use, and mortalities caused by energy infrastructure (Ogada et al. 2016a,b). One of the least known anthropogenic threats to African vultures is mortality caused by captive big cats, *Panthera* spp. (Mundy et al. 1992). Here we describe a case of captive big cats (lions, *Panthera leo*, and leopards, *P. pardus*) killing Critically Endangered vultures when they land in enclosures at a predator breeding tourist facility in South Africa close to protected areas where vultures occur. In light of rapid population declines (Thiollay 2006; Virani et al. 2011; Buechley & Şekercioğlu 2016), and the dire conservation status of most African vulture species (IUCN 2018), we aim to highlight this source of mortality in Critically Endangered vultures. We hope that this record will serve as motivation for further investigation into the spatial extent and magnitude of this source of mortality and, if necessary, mitigation of this potential threat.

Observations

On 13 October 2016, Lindy Thompson observed a dead Cape Vulture (*Gyps coprotheres*) in a supplementary feeding site at an endangered species centre in South Africa's Limpopo Province (Figure 1). Since Thompson did not know how the bird came to be there, she emailed an enquiry to the centre, asking them to remove the bird to reduce the spread of possible pathogens or poison to other scavengers. The same day, Thompson received a reply from one of the centre's staff members, saying that the vulture had been killed by one of their predators and the carcass disposed of at the feeding site.

On 4 January 2018, John Davies received a report from a member of the public who had visited the same facility on the previous day that said that two of the centre's captive leopards were killing free-ranging vultures that landed in their enclosure. Note that we wish to highlight a source of mortality to vultures, rather than condemn a particular facility, and so we do not mention the property by name nor its exact geographical location. Thompson immediately arranged to meet a staff member at this facility, who stated that the centre's big cats were killing vultures at a rate of approximately one per month. A few days later, at a second meeting, the facility's manager told Thompson that the big cats in two enclosures (each 1 hectare) were exhibiting this behaviour: the first enclosure housed two lions, and the second housed two leopards. These particular big cats were repeatedly catching and killing (but not eating) vultures that landed in their enclosures to bathe in the cats' drinking water and to feed on food scraps (and possibly also faeces, in the case of Hooded Vultures (*Necrosyrtes monachus*) (Mundy et al. 1992; Reading et al. 2017)). A former staff member of the centre later told Thompson that lions at this facility used to kill two to three vultures (Hooded and White-backed) a month, and, while those lions were now deceased, the lions currently at the facility also display this behaviour. The two aforementioned vulture species are classified both globally and regionally as Critically Endangered (Taylor et al. 2015; IUCN 2018).

In an attempt to determine how widespread this phenomenon is, we interviewed staff at 11 predator parks and lion hunting ranches in South Africa, and obtained responses from seven facilities. The people we interviewed had worked at these seven facilities for an average 17.3 ± 18.7 years (mean ± standard deviation, n = 6), with a combined work experience of at least 104 years. Three of these seven individuals had never encountered their captive predators chasing or killing birds (at predator parks in Gauteng, the Eastern Cape

Figure 1. A Cape Vulture killed by a captive predator at a facility in Limpopo Province, South Africa, and placed at the centre's supplementary feeding site. Photographed on 13 October 2016, by L.J. Thompson.

and Limpopo). The remaining four people we spoke to had observed the following: leopards and cheetahs (*Acinonyx jubatus*) rarely killing Yellow-billed Kites (*Milvus aegyptius*) and Helmeted Guineafowl (*Numida meleagris*) (at a tourist facility in Limpopo); a lion catching (but not killing) a juvenile Verreaux's Eagle (*Aquila verreauxii*) (at a tourist facility in KwaZulu-Natal), lions killing White-backed Vultures and crows (*Corvus sp*.) (at an unrecorded frequency at a lion hunting ranch in North West Province); and lions killing one vulture (species unknown) and one crow (at a lion hunting ranch in North West Province). These observations suggest that captive predators may kill wild vultures and other birds at other facilities, and this behavior may be widespread across various provinces, but that it is also rare.

Discussion

Large mammalian scavengers and predators such as lion, leopard, cheetah and African wild dog (*Lycaon pictus*) do not tolerate vultures approaching too closely (or feeding) when they are feeding (Attwell 1963). Wild lions and African wild dogs frequently chase vultures (including Hooded and White-backed vultures) off carcasses, but it seems that vultures are rarely caught and killed (Attwell 1963; Mundy 1997). Hooded Vultures may be drawn to the lions' enclosure for food scraps (including moist lion droppings), and White-backed Vultures have previously been observed visiting the enclosures of captive lions to scavenge on food remains (Mundy et al. 1992). We could find little evidence of an association between wild leopards and vultures in the scientific literature (Kendall et al. 2012), other than leopards killing and predating on Lappet-faced and White-backed vulture nestlings (Pennycuick 1976; Mundy et al. 1992; Pringle 2016; Grobler 2018). Leopards usually consume small prey animals immediately after killing them, and cache larger prey in dense trees where they cannot be found by vultures and mammalian scavengers (Kruuk & Turner 1967). Therefore, the captive leopards at this facility seem to be displaying an unusual behaviour when they kill vultures.

The reported current loss of at least one individual vulture per month at this facility equates to a conservative estimate of 12 White-backed and/or Hooded vultures killed at this centre per year. In South Africa, there are an estimated 100–200 mature Hooded Vultures and 3 435 breeding pairs of White-backed Vultures (Taylor et al. 2015). The annual loss of vultures at this facility is therefore significant, and represents an additional and ongoing threat to the region's vulture populations. This facility is 30 km from a core Hooded Vulture breeding area (Thompson et al. 2017), 2.9 km from the nearest known Hooded Vulture nest (Davies, pers. obs.), and 13 km from the Kruger National Park, which holds an internationally significant population of White-backed Vultures (Murn et al. 2013). These distances of source vulture areas to the facility are well within the daily distances travelled by Hooded and White-backed vultures (Phipps et al. 2013; Reading et al. 2019), the two vulture species commonly being killed at this centre.

Thompson's suggestion of installing roofs over the big cats' enclosures to prevent vultures from landing, was dismissed by the centre's management for being too expensive, and because roofs would make the enclosures 'look too much like cages', which would be unsightly for paying guests. Our repeated requests to spend a day observing the big cats in question, aiming to better understand the problem, were denied by the facility. The centre's policy of discarding leftover meat and bones at two sites on the property, for free-roaming vultures to consume, may be compounding this problem. One of these sites is a dump, and the other is a supplementary feeding site that is open for public viewing. The daily congregation of hundreds of Endangered and Critically Endangered vultures at this property's feeding sites (Thompson pers. obs.) may be a 'source', facilitating an ongoing supply of highly threatened birds to the 'sinks' that are the big cat enclosures.

Conservation recommendations

It is imperative that owners and staff of centres such as this, where captive big cats are killing highly threatened vultures, recognise the conservation implications of this phenomenon. Such cases should be reported to the relevant local wildlife authorities by anyone (including researchers, staff members, managers, owners, veterinarians, volunteers, tradesmen and members of the public) who becomes aware of it, so that it can be swiftly and effectively dealt with. The simplest solution may be for facility staff to make use of the smaller feeding enclosures within the big cat enclosures. These smaller feeding enclosures have doors and roofs, which prevent vultures from entering these designated feeding areas. While the big cats feed in the small, contained feeding enclosures, staff could remove all food scraps and faeces from the rest of the enclosures, minimising the attraction for vultures and preventing the problem. At the facility in question, staff do not make use of the feeding enclosures, instead they allow the big cats to drag their food out into the larger, uncovered enclosures, where it attracts vultures. Other management tools could include a variety of environmental enrichment techniques for captive big cats (Powell 1995; Bashaw et al. 2003; Clark & King 2008; Sutherland et al. 2018), coupled with exclusion techniques and/or visual deterrents, such as human disturbance, to prevent vultures from landing in big cats' enclosures (Bishop et al. 2003). We further recommend that centres place supplementary feeding sites for vultures as far as possible from uncovered big cat enclosures, to reduce the possibility of attracting vultures to these enclosures. As a last resort, we suggest the relocation of the problem big cats to another facility outside of vulture foraging range.

We suggest that regulatory authorities who are responsible for issuing permits to allow such facilities to operate (provincial conservation agencies in the case of South Africa) should impose permit conditions to minimise the risk of vulture mortality at predator facilities. This could include measures such as requiring the covering of enclosures if other effective management options cannot be implemented. It may also include prohibition of additional facilities within the foraging range of Critically Endangered and Endangered vulture species, unless clear measures are taken to reduce such anthropogenically induced mortality.

Finally, we encourage researchers to assess the spatial extent of this problem and the frequency with which it occurs, to determine the potential population-level impact of this poorly documented threat to African vultures.

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References

Attwell, R.I.G., 1963, 'Some observations on feeding habits, behaviour and inter-relationships of northern Rhodesian vultures', *Ostrich* 34, 235–247, https://doi.org/10.1080/00306525.1963.9633479.

Bashaw, M.J., Bloomsmith, M.A., Marr, M.J. & Maple, T.L., 2003, 'To hunt or not to hunt? A feeding enrichment experiment with captive large felids', *Zoo Biology* 22, 189–198, https://doi.org/10.1002/zoo.10065.

Bishop, J., McKay, H., Parrott, D. & Allan, J., 2003, 'Review of international research literature regarding the effectiveness of auditory bird scaring techniques and potential alternatives', Central Science Laboratories for the Department for Environmental Food and Rural Affairs, London, UK.

Buechley, E.B. & Şekercioğlu, C., 2016, 'The avian scavenger crisis: Looming extinctions, trophic cascades, and loss of critical ecosystem functions', *Biological Conservation* 198, 220–228, DOI: 10.1016/j.biocon.2016.04.001.

Clark, F. & King, A.J., 2008, 'A critical review of zoo-based olfactory enrichment', in 'Chemical signals in vertebrates 11'. Eds J.L. Hurst, R.J. Beynon, S.C. Roberts, and T.D. Wyatt. Springer: New York, NY.

Grobler, R., 2018, 'Curiosity killed the … vulture?' viewed 13 April 2019, from https://www.lionsands.com/2018/09/curiosity-killed-vulture-leopard/#.

IUCN, 2018, 'The IUCN Red List of Threatened Species', version 2018-1. www.iucnredlist.org. Downloaded on 10 August 2018.

Kendall, C., Virani, M.Z., Kirui, P., Thomsett, S. & Githiru, M., 2012, 'Mechanisms of coexistence in vultures: understanding the patterns of vulture abundance at carcasses in Masai Mara National Reserve, Kenya', *Condor* 114, 523–531, DOI: 10.1525/cond.2012.100196.

Kruuk, H. & Turner, M., 1967, 'Comparative notes on predation by lion, leopard, cheetah and wild dog in the Serengeti area, East Africa', *Mammalia* 31, 1–27.

Mundy, P.J., 1997, 'Hooded Vulture *Necrosyrtes monachus*', in 'The atlas of southern African birds'. Eds J.A. Harrison, D.G. Allan, L.G. Underhill, M. Herremans, A.J. Tree, V. Parker, and C.J. Brown. pp. 156–157. BirdLife South Africa: Johannesburg.

Mundy, P.J., Butchart, D., Ledger, J. & Piper, S., 1992, 'The vultures of Africa', Academic Press: London, UK.

Murn, C., Combrink, L., Ronaldson, G.S., Thompson, C. & Botha, A., 2013, 'Population estimates of three vulture species in Kruger National Park, South Africa', *Ostrich* 84, 1–9, https://doi.org/10.2989/00306525.2012.757253.

Oaks, J.L., Gilbert, M., Virani, M.Z., Watson, R.T., Meteyer, C.U., Rideout, B.A., Shivaprasad, H.L., Ahmed, S., Chaudry, M.J.I., Arshad, M., Mahmood, S., Ali, A. & Khan, A.A. 2004, 'Diclofenac residues as the cause of vulture population decline in Pakistan', *Nature* 427, 630–633, https://doi.org/10.1038/nature02317.

Ogada, D., Botha, A. & Shaw, P., 2016a, 'Ivory poachers and poison: drivers of Africa's declining vulture populations', *Oryx* 50, 593–596, https://doi.org/10.1017/S0030605315001209

Ogada, D., Shaw, P., Beyers, R.L., Buij, R., Murn, C., Thiollay, J.M., Beale, C.M., Holdo, R.M., Pomeroy, D., Baker, N., Kruger, S.C., Botha, A., Virani, M.Z., Monadjem, A. & Sinclair, A.R.E., 2016b, 'Another continental vulture crisis: Africa's vultures collapsing toward extinction', *Conservation Letters* 9, 89–97.

Pennycuick, C.J., 1976, 'Breeding of the Lappet-faced and White-headed vultures (*Torgos tracheliotus* Forster and *Trigonoceps occipitalis* Burchell) on the Serengeti Plains, Tanzania', *African Journal of Ecology* 14, 67–84.

Phipps, W.L., Willis, S.G., Wolter, K. & Naidoo, V., 2013, 'Foraging ranges of immature African White-backed Vultures (*Gyps africanus*) and their use of protected areas in southern Africa', *PLoS ONE* 8, e52813, https://doi.org/10.1371/journal.pone.0052813.

Powell, D.M., 1995, 'Preliminary evaluation of environmental enrichment techniques for African lions (*Panthera leo*)', *Animal Welfare* 4, 31–370.

Pringle, G., 2016, 'Kruger leopard with a head for heights', viewed 13 April 2019, from https://www.wildcard.co.za/kruger-leopard-head-heights/.

Reading, R., Tshimologo, B. & Maude, G., 2017, 'Coprophagy of African Wild Dog faeces by Hooded Vultures in Botswana', *Vulture News* 72, 34–37.

Reading, R., Bradley, J., Hancock, P., Garbett, R., Selebatso, M. & Maude, G., 2019, 'Home range size and movement patterns of Hooded Vultures *Necrosyrtes monachus* in southern Africa', *Ostrich* 90, 73–77, DOI: 10.2989/00306525.2018.1537314.

Sutherland, W.J., Dicks, L.V., Ockendon, N., Petrovan, S.O. & Smith, R.K. (Eds.), 2018, 'What works in conservation'. OpenBook Publishers.

Taylor, M.R., Peacock, F. & Wanless, R.M., 2015, 'The 2015 Eskom Red Data Book of birds of South Africa, Lesotha and Swaziland'. BirdLife South Africa: Johannesburg.

Thiollay, J.-M., 2006, 'Severe decline of large birds in the Northern Sahel of West Africa: A long-term assessment', *Bird Conservation International* 16, 353–365.

Thompson, L.J., Davies, J.P., Gudehus, M., Botha, A.J., Bildstein, K.L., Murn, C. & Downs, C.T., 2017, 'Visitors to nests of Hooded Vultures *Necrosyrtes monachus* in north-eastern South Africa', *Ostrich* 88, 155–162, http://dx.doi.org/10.2989/00306525.2017.1321049.

Virani, M.Z., Kendall, C., Njoroge, P. & Thomsett, S., 2011, 'Major declines in the abundance of vultures and other scavenging raptors in and around the Masai Mara ecosystem, Kenya', *Biological Conservation* 144, 746–752, https://doi.org/10.1016/j.biocon.2010.10.024.

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Senecio cymbalarifolius (L.) Less. is the correct name for *S. sonchifolius* (L.) J.C.Manning & Magoswana, nom. illeg. and clarification of the name *S. sonchifolius* (L.) Moench (Asteraceae: Senecioneae)

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Background: Ongoing systematic studies in the African flora necessitate periodic nomenclatural adjustments and corrections.

Objectives: To effect requisite nomenclatural changes.

Method: Relevant literature was surveyed and type material located and examined.

Results: The combination *Senecio sonchifolius* (L.) J.C.Manning & Magoswana (2017), based on *Othonna sonchifolia* L., is an illegitimate later homonym for *S. sonchifolius* (L.) Moench (1802).

Conclusions: The name *Senecio cymbalarifolius* (L.) Less. is the earliest legitimate name in *Senecio* for the taxon previously known as *S. sonchifolius* (L.) J.C.Manning & Magoswana, nom. illeg. On internal evidence, we conclude that *S. sonchifolius* (L.) Moench was intended as a combination based on *Cacalia sonchifolia* L. and that the citation of the basionym as *Cineraria sonchifolia* L. was an error.

Introduction

The combination *Senecio sonchifolius* (L.) J.C.Manning & Magoswana was recently published as the avowed correct name for *Senecio cymbalarifolius* (L.) Less., resulting from the conclusion that the basionym *O. sonchifolia* L. represented the earliest validly published name for the taxon (Magoswana et al. 2017). Unfortunately it now emerges that this combination is preoccupied by the earlier, heterotypic combination *S. sonchifolius* (L.) Moench (1802), rendering *S. sonchifolius* (L.) J.C.Manning & Magoswana an illegitimate later homonym (Turland et al. 2018: Art. 53.1). The next available name for the species in *Senecio* is *S. cymbalarifolius* (L.) Less. (Lessing 1832) (Turland et al. 2018: Art. 11.4, Ex. 17), which therefore continues to be the correct name for the taxon in that genus. Should the taxon be treated in another genus, however, the earlier *O. sonchifolia* L. (Linnaeus 1753) remains available.

There is, however, a slight complication in the status of *Senecio sonchifolius* (L.) Moench [currently treated as *Emilia sonchifolia* (L.) DC.], which was published in the *Supplementum ad Methodum Plantas*… (Moench, 1802) with a reference to '*Cineraria, sonchifolia* Murray Comment. Goett. Nov. T. III. p. 79. icon. t. 7' (Fig. 1). This is a reference to J.A. Murray's *Observationes*… (Murray 1773). The entry in question in Murray (1773) is, however, actually to *Cacalia sonchifolia* L. (Fig. 2), with an indirect reference to this name in the *Species plantarum* (Linnaeus

1753) (Fig. 3). The simplest interpretation is that Moench (1802) intended his name to be a combination in *Senecio* based on *Cacalia sonchifolia* L. (1753) but erred in citing Murray's (1773) entry as *Cineraria* instead of *Cacalia*. This interpretation is consistent with the description of the taxon by Moench (1802) as having erect capitula, with nodding florets in the detached capitulum ['*capitulis floriferis erectis, defloratis nutantibus*.']. The apparently nodding florets in the detached capitulum, which match the illustration in Murray (1773) perfectly, are evidently an abnormality resulting from damage as they are not seen in the representation of the intact capitula. This is compelling internal evidence that Moench (1802) intended his name to apply to the plant depicted by Murray (1773). His error in the citation of the generic name does not affect the validity of the combination (Turland et al. 2018: Art. 41.3).

An alternative interpretation is that the citation by Moench (1802) of '*Cineraria, sonchifolia* …' constitutes an indirect reference to the name *Cineraria sonchifolia* (L.) L., a combination published by Linnaeus (1763) based on *Othonna sonchifolia* L. (1753). While this interpretation would be nomenclaturally arguable, it is untenable in our opinion, given both the precise pagination of the Murray (1773) citation and the exact correspondence between the description by Moench (1802) and the illustration published by Murray (1773). On this basis we are confident that Moench (1802) intended his name to apply to the disciform taxon figured by Murray (1773) under the name *Cacalia sonchifolia* and not to the radiate *Cineraria sonchifolia*. We therefore accept the name published by

SENECIO, *fonchifolius*, caule herbaceo, foliis amplexicaulibus ovato-lanceolatis, fubdentatis, capitulis floriferis erectis, defloratis nutantibus.
Cineraria, *fonchifolia*. *Murray Comment. Goett. nov.* T. III. p. 79. *icon. t.* 7.

Figure 1. *Senecio sonchifolius* from Moench, *Supplementum ad Methodum Plantas*…: 231 (1802).

9.
Cacalia fonchifolia L.
CACALIA *caule herbaceo, foliis lyratis amplexicaulibus dentatis* LINN. *Syft. nat. Tom.* 2. *p.* 535. *Sp. plant. p.* 1169. *Mant.* 2. *p.* 463.

Figure 2. *Cacalia sonchifolia* L. from Murray, *Novi commentarii Societatis Regiae Scientiarum Gottingensis* 3: 79 (1773).

6. CACALIA caule herbaceo, foliis lyratis dentatis. *Sonchifolia.*
Kleinia caule herbaceo, foliis lyratis. *Fl. zeyl.* 305. *
Chondrilla zeylanica minor marina, folio finapios. *Burm. zeyl.* 61.
Tagolina luzonum, flore purpureo. *Pet. gaz. t.* 80. *f.* 13. *Camell. luz.* 3. *n.* 8.
Habitat in Zeylona, China. ☉.

Figure 3. *Cacalia sonchifolius* from Linnaeus, *Species plantarum* 2: 835 (1753).

Moench (1802) as a combination based on *Cacalia sonchifolia* L. (1753).

Should there have been no internal evidence favouring one of the interpretations over the other, i.e. that there was no single clear reference to a basionym, then the name *Senecio soncifolia* published by Moench (1802) would have been validly published as a new species. Any of the three possibilities still renders the later combination *S. sonchifolius* (L.) J.C.Manning & Magoswana illegitimate.

Materials and methods

All relevant literature and type material was examined. Herbarium acronyms after Thiers (2015).

Nomenclature

Senecio cymbalarifolius (L.) Less., Syn. Gen. Compos.: 391 (1832). *Othonna cymbalarifolia* L., Pl. Rar. Afr.: 24 (1760). *Cineraria cymbalarifolia* (L.) L., Sp. Pl. ed. 2, 2: 1242 (1763). *Brachyrhynchos cymbalarifolius* (L.) DC., Prodr. 6: 438 (1838). Type: South Africa, 'Cap Bonae Spei', without date, *Oldenland s.n.* (G–herb. Burm. G00818194—image!, lecto., designated by Magoswana et al. in Bothalia 47(1)-a2213: 4 (2017).

Othonna sonchifolia L., Sp Pl. 2: 924 (1753) [non *O. sonchifolia* DC., Prodr. 6: 482 (1838), nom. illeg. = *O. bulbosa* L. (1753)]. *Cineraria sonchifolia* (L.) L., Sp. Pl. ed. 2, 2: 1243 (1763). *Doria sonchifolia* (L.) Thunb., Nov. Gen. Pl.: 167 (1800). *Senecio sonchifolius* (L.) J.C.Manning & Magoswana in Bothalia 47(1)-a2213: 4 (2017), nom. illeg. [non *S. sonchifolius* (L.) Moench, Suppl. Meth.: 223 (1802)]. Type: South Africa, without precise locality or date, *Oldenland s.n.,* illustration in Breyne, Prodr. Fasc. Rar. Pl.: 31 t. 21, f.1 (1739).

Emilia sonchifolia (L.) DC. in Wight, Contr. Bot. India: 24 (1834). *Cacalia sonchifolia* L., Sp. Pl. 2: 853 (1753). *Senecio sonchifolius* (L.) Moench [basionym incorrectly cited as *Cineraria sonchifolia*], Suppl. Meth.: 231 (1802). Type: 'habitat in Zeylona, China', [BM, herb. Hermann 2: 25, 4: 36, 4:66, no. 305 (multiple sheets of a single gathering), lecto., designated by Grierson in Dassanayke, Revised Handb. Fl. Ceylon 1: 252 (1980)].

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References

Breyne, J., 1739, *Prodomi Fasciculi Rariorum Plantarum Primus et Secundus*. J.P. Breyne, Danzig.

Candolle, A.P. de, 1838, 'Compositae', *Prodromus* vol. 6, Teuttel & Würtz, Paris.

Lessing, C.F., 1832. *Synopsis generum Compositarum*, Duncker & Humblot, Berlin.

Linnaeus, C., 1753, *Species plantarum*, Salve, Stockholm.

Linnaeus, C., 1760, *Plantae rariores africanae*, Holm, Stockholm.

Linnaeus, C., 1763. *Species plantarum,* edn 2, Salve, Stockholm.

Magoswana, S.L., Manning, J.C., Magee, A.R. & Boatwright, J.S., 2017, '*Othonna sonchifolia* L. is an earlier name for *Senecio cymbalarifolius* L. (Asteraceae: Senecioneae)', *Bothalia* 47(1)-a2213: 1–4. https://doi.org/10.4102/abc.v47i1.2213.

Moench, C ., 1802, *Supplementum ad Methodum Plantas*. J.W. Landon (inf.), Marburg.

Murray, J.A., 1773, 'Observationes super stirpibus quibusdam recens inventibus et rarioribus in horto academico institutae', *Novi commentarii Societatis Regiae Scientiarum Gottingensis* 3: 60–84.

Dassanayke, M.D., 1980, *A Revised Handbook to the Flora of Ceylon*, vol. 1. Amerind Publishing Co., New Delhi.

Thiers, B., 2015, 'Index Herbariorum: A global directory of public herbaria and associated staff', New York Botanical Garden's Virtual Herbarium (Accessed 2015/10/20. http://sweetgum.nybg.org/ih/).

Thunberg, C.P., 1800, *Nova genera plantarum* 12. Edman, Uppsala.

Turland, N.J., Wiersema, J.H., Barrie, F.R., Greuter, W., Hawksworth, D.L., Herendeen, P.S., Knapp, S., Kusber, W.-H., Li, D.-Z., Marhold, K., May, T.W., McNeill, J., Monro, A.M., Prado, J., Price, M.J. & Smith, G.F. (eds.), 2018, 'International Code of Nomenclature for algae, fungi, and plants (Shenzhen Code) adopted by the Nineteenth International Botanical Congress Shenzhen, China, July 2017', *Regnum Vegetabile* 159. Glashütten: Koeltz Botanical Books. DOI https://doi.org/10.12705/Code.

Wight, R., 1834, *Contributions to the botany of India*. Parbury, Allen & Co., London.

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Validation of *Massonia* sect. *Whiteheadia* (Hyacinthaceae: Scilloideae)

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Abstract: The invalidly published name *Massonia* sect. *Whiteheadia* (Harv.) J.C.Manning is validated.

Keywords: Africa; invalid name; nomenclature; taxonomy.

Introduction

The genus *Massonia* Thunb. ex Houtt. (Hyacinthaceae: Scilloideae) comprises ± 30 species of southern African geophytes, concentrated in the winter-rainfall parts of the region. In the recent account of the species for the Cape Floristic Region, Manning (2019) divided the genus into three sections. Due to a page-setting error one of these sectional names was not validly published and is validated here.

Nomenclature

The combination *Massonia* sect. *Whiteheadia* was published by Manning (2019) for the single species *Massonia bifolia* (Jacq.) J.C.Manning & Goldblatt. Unfortunately the basionym citation was partially ommitted, rendering the name invalidly published according to Art. 41.5 of the *International Code of Nomenclature for fungi, algae and plants* (Turland et al. 2018), which states that 'On or after 1 January 2007, a new combination, name at new rank, or replacement name is not validly published unless its basionym or replaced synonym is cited.' The full, validating citation is provided here.

Massonia sect. **Whiteheadia** *(Harv.) J.C.Manning*, stat. et comb. nov. *Whiteheadia* Harv., The Genera of South African Plants, edn. 2: 396 (1868).

References

Manning, J.C. 2019. The genus *Massonia* Thunb. ex Houtt. (Hyacinthaceae: Scilloideae) in the Core Cape Floristic Region. *South African Journal of Botany* 121: 329–354, DOI: 10.1016/j.sajb.2018.11.015

Harvey, W.H. 1868. *The Genera of South African Plants*, edn. 2. Juta, Cape Town.

Turland, N.J., Wiersema, J.H., Barrie, F.R., Greuter, W., Hawksworth, D.L., Herendeen, P. S., Knapp, S., Kusber, W.-H., Li, D.-Z., Marhold, K., May, T.W., McNeill, J., Monro, A.M., Prado, J., Price, M.J. & Smith, G.F. (eds.) 2018: *International Code of Nomenclature for algae, fungi, and plants (Shenzhen Code) adopted by the Nineteenth International Botanical Congress Shenzhen, China, July 2017*. Regnum Vegetabile 159. Glashütten: Koeltz Botanical Books.

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The correct author citation for Jacquin's names in *Drimia* (Hyacinthaceae: Urgineoideae) and *Eriospermum* (Ruscaceae)

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The correct author citations for several names in the genera *Drimia* (Hyacinthaceae) and *Eriospermum* (Ruscaceae) that were invalidly published by N.J. Jacquin are provided. The later validation dates for these names do not have implications for their nomenclatural priority.

Keywords: Africa; invalid name; nomenclature; taxonomy; Willdenow

Introduction

The recent account of *Drimia* (Hyacinthaceae: Urgineoideae) in southern Africa by Manning and Goldblatt (2018) recognised 70 species in the first complete regional review of this ethno-botanically important genus since the earlier partial reviews of species by Nordenstam (1970) and Jessop (1977). As such, it will certainly be treated as a primary resource for the taxonomy of the group for some time. It is thus especially unfortunate that the authors erred in their interpretation of the validating authors for the generic name and some associated species described by Jacquin (1795). A similar error made by Perry (1994) in her monograph of the genus *Eriospermum* (Ruscaceae), which comprises some 104 species distributed throughout sub-Saharan Africa, has remained undetected until now. These errors are corrected here.

Nomenclature

The name *Drimia* was first published by Jacquin (1795) in his *Icones plantarum rariorum* for five species of southern African Hyacinthaceae with reflexed tepals. Although the individual species were described, no separate generic description or diagnosis was included, either then or later in his *Collectaneorum supplementum* (Jacquin 1797). This lack of a diagnosis for his new genus, which included more than a single species at the time, renders the generic name invalid (Turland et al. 2018: Art. 38.1, 38.5), and this in turn renders the names of the five species published by him under that genus also invalid (Turland et al, 2018: Art. 35.1). The attribution by Manning and Goldblatt (2018) of the generic name *Drimia* and its five original species to Jacquin as the author is thus incorrect. All these names were in fact only validated by Willdenow (1799) in *Species plantarum*, ed. 4 through his provision of a descriptions for the genus as well as the individual species.

In like manner, Jacquin (1795) published three species in the new genus *Eriospermum* in *Icones plantarum rariorum* and subsequently in *Collectaneorum* *supplementum* (Jacquin 1797), followed by a further two species in *Plantarum rariorum horti caesarei schoenbrunnensis* (Jacquin 1798). Once again no separate generic description or diagnosis was provided in any of these publications, rendering the generic name invalid (Turland et al. 2018: Art. 38.1, 38.5), and thus in turn the names of the five species published by him under that genus (Turland et al. 2018: Art. 35.1). As in *Drimia*, the genus *Eriospermum* and its initial three species were validated by Willdenow (1799) in the *Species plantarum*, ed. 4, and these names are thus to be attributed to Willdenow. The remaining two species described by Jacquin (1798) were not included in Willdenow (1799) and their validation dates from their publication by Ker Gawler (1811) in *The Botanical Register*. Although Perry (1994) correctly attributed the genus *Eriospermum* to Willdenow (1799), she overlooked the nomenclatural complications for the five species described by Jacquin.

The correct author citations for all of these names are provided here. Currently accepted names are given in **bold**. Fortunately the slightly later dates for the validation of these names have no implication on nomenclatural priority for the taxa concerned.

Drimia *Jacq. ex Willd.*, Sp. Pl. 2: 165 (1799).

[*Drimia* Jacq., nom. inval., without description, Icones Pl. Rar. 2 (1795); Collect. Suppl. (1797).]

Drimia elata *Jacq. ex Willd.*, Sp. Pl. 2: 165 (1799).

[*Drimia elata* Jacq., nom. inval., without generic description, Icones Pl. Rar. 2: 15, t. 373 (1795); Collect. Suppl.: 38 (1797).]

Drimia ciliaris Jacq. ex Willd., Sp. pl. 2: 165 (1799).

[*Drimia ciliaris* Jacq., nom. inval., without generic description, Icones Pl. Rar. 2: 15, t. 377 (1795); Collect. suppl.: 41 (1797).]

Note: This taxon is considered to be conspecific with **D. elata** Jacq. ex Willd. (Manning & Goldblatt 2018).

Drimia pusilla Jacq. ex Willd., Sp. pl. 2: 165 (1799).

[*Drimia pusilla* Jacq., nom. inval., without generic description, Icones Pl. Rar. 2: 15, t. 374 (1795); Collect. Suppl.: 42 (1797).]

Note: This taxon is considered to be conspecific with **D. elata** Jacq. ex Willd. (Manning & Goldblatt 2018).

Drimia media *Jacq. ex Willd.*, Sp. pl. 2: 166 (1799).

[*Drimia media* Jacq., nom. inval., without generic description, Icones Pl. Rar. 2: 15, t. 375 (1795); Collect. Suppl.: 40 (1797).]

Drimia undulata Jacq. ex Willd., Sp. pl. 2: 166 (1799).

[*Drimia undulata* Jacq., nom. inval., without generic description, Icones Pl. Rar. 2: 15, t. 376 (1795): Collect. Suppl.: 41 (1797).]

Note: This is the basionym of **Ledebouria undulata** *(Jacq. ex Willd.) Jessop* (Jessop, 1970).

Eriospermum *Jacq. ex Willd.*, Sp. pl. 2: 110 (1799).

[*Eriospermum* Jacq., nom. inval., without description, Icones Pl. Rar. 2 (1795); Collect. Suppl. (1797).]

Eriospermum lanceifolium *Jacq. ex Willd.* [as '*lanceaefolium*'], Sp. Pl. 2: 111 (1799).

[*Eriospermum lanceaefolium* Jacq., nom. inval., without generic description, Icones Pl. Rar. 2: 19, t. 421 (1795); Collect. Suppl.: 72 (1797).]

Eriospermum lanuginosum *Jacq. ex Ker Gawl.* in Curtis's Bot. Mag. 34: sub. t. 1382 (1811); [Edwards] Bot. Reg. 7: sub. t. 578 (1821).

[*Eriospermum lanuginosum* Jacq., nom. inval., without generic description, Pl. Rar. Hort. Schoenbr. 3: 7, t. 264 (1798).]

Eriospermum latifolium Jacq. ex Willd., Sp. pl. 2: 110 (1799).

[*Eriospermum latifolium* Jacq., nom. inval., without generic description, Icones Pl. Rar. 2: 18, t. 420 (1795); Collect. Suppl.: 73 (1797).]

Note: This taxon is considered to be conspecific with *E. capense* (L.) Thunb. (Perry, 1994).

Eriospermum parvifolium *Jacq. ex Willd.*, Sp. pl. 2: 111 (1799).

[*Eriospermum parvifolium* Jacq., nom. inval., without generic description, Icones Pl. Rar. 2: 19, t. 422 (1795); Collect. Suppl.: 74 (1797).]

Eriospermum pubescens *Jacq. ex Ker Gawl.* in Curtis's Bot. Mag. 34: sub. t. 1382 (1811); [Edwards] Bot. Reg. 7: t. 578 (1821).

[*Eriospermum pubescens* Jacq., nom. inval., without generic description, Pl. Rar. Hort. Schoenbr. 3: 8, t. 265 (1798).]

References

Jacquin, N.J., 1795, Icones plantarum rariorum, vol. 2, Wappler, Vienna etc.

Jacquin, N.J., 1797, Collectaneorum supplementum, Wappler, Vienna.

Jacquin, N.J., 1798, Plantarum Rariorum Horti Caesarei Schoenbrunnensis, vol. 3, Wappler, Vienna etc.

Jessop, J.P., 1970, 'Studies in the bulbous Liliaceae 1: *Scilla*, *Schizocarphus* and *Ledebouria*', *Journal of South African Botany* 36: 233–266.

Jessop, J.P., 1977, Studies in the bulbous Liliaceae 7: The taxonomy of *Drimia* and certain allied genera', *Journal of South African Botany* 43: 265–319.

Ker Gawler, J.B., 1811, '*Eriospermum latifolium*. Short-pedicled broad-leaved *Eriospermum*', Curtis's Botanical Magazine 34: t. 1382.

Ker Gawler, J.B., 1821, '*Eriospermum pubescens*', *The Botanical Register* 7: t. 578.

Manning, J.C. & Goldblatt, P., 2018, 'Systematics of *Drimia* Jacq. (Hyacinthaceae: Urgineoideae) in southern Africa', *Strelitzia* 40. South African National Biodiversity Institute, Pretoria.

Nordenstam, B., 1970, 'Studies in South African Liliaceae 3: The genus *Rhadamanthus*', *Botaniska Notiser* 123: 155–182.

Perry, P.L., 1994, 'A revision of the genus *Eriospermum* (Eriospermaceae)', *Contributions of the Bolus Herbarium* 17: 1–320.

Turland, N.J., Wiersema, J.H., Barrie, F.R., Greuter, W., Hawksworth, D.L., Herendeen, P.S., Knapp, S., Kusber, W.-H., Li, D.-Z., Marhold, K., May, T.W., McNeill, J., Monro, A.M., Prado, J., Price, M. J. & Smith, G.F. (eds.), 2018, 'International Code of Nomenclature for algae, fungi, and plants (Shenzhen Code) adopted by the Nineteenth International Botanical Congress Shenzhen, China, July 2017', *Regnum Vegetabile* 159. Glashütten: Koeltz Botanical Books.

Willdenow, C.L., 1799, Species plantarum, ed. 4, vol. 2, Nauk, Berlin.

BOTHALIA – African Biodiversity & Conservation
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Guidelines for authors

These guidelines provide an overview of the structure and style of articles to be submitted to the South African National Biodiversity Institute (SANBI)'s peer-reviewed journal:
Bothalia – African Biodiversity & Conservation.

TYPES OF ARTICLES

Full length articles report on complete, comprehensive pieces of original research, as well as reviews, strategies or innovative case studies in any field of work aligned with the scope of the journal. Full length articles include a maximum of 8 000 words and 60 references.

Short communications are concise reports on narrow investigations. These include new species descriptions. They have a maximum of 2 000 words and 30 references.

In the case of reviews, strategies and short communications, not all of the headings and subheadings specified below may be relevant. In such cases authors will need to use their discretion in selecting appropriate headings.

FORMATTING

Manuscripts must be submitted as a MS Word document. Documents compiled in other software, including Google Documents, cannot be accepted.

Low resolution versions of figures and tables can be inserted into the document. High resolution of figures must, however, also be included separately, with each figure as a separate, appropriately labelled file (see details of requirements for figures below).

Please do not use hidden formatting, including character styles in the manuscript. Also avoid nested tables and text boxes. Many of these cause corruptions in the design software, and can usually be avoided if authors refrain from copying and pasting from various sources, including other MS Word documents.

- **Language:** Manuscripts must be written in British English. Avoid Americanisms (e.g. use 's' and not 'z'). Consult the Oxford English Dictionary when in doubt and remember to set your version of Microsoft Word to UK English.
- **Line numbers:** Insert continuous line numbers.
- **Font:**
  - **Font type:** Times New Roman
  - **General font size:** 12pt
- **Line spacing:** 1.15
- **Headings:** Ensure that formatting for headings is consistent in the manuscript.
  - First headings: normal, bold and 14pt
  - Second headings: normal, bold and 12pt
  - Third headings: normal, underlined and 12pt
  - Fourth headings: normal, bold, running-in text and separated by a colon, and 12pt.

Scientific names: Names of genera and infrageneric taxa are italicised, with the author citation not italicised. Exceptions include specific cases in taxonomic treatments (see details of such manuscripts below); new taxa in the abstract; and in checklists where the position is reversed – correct names are not italicised and synonyms are italicised. Names above generic level are not italicised. The complete scientific name of a species as well as the author citation should be given at the first mention in the text. The generic names should be abbreviated to the initial thereafter, except where references to other genera with the same initial could cause confusion.

Authors of botanical names are abbreviated according to Authors of Plant Names (Brummitt & Powell 1992, Royal Botanic Gardens, Kew).

In names covered by the International Code of Zoological Nomenclature, the date of publication should be separated from the authority by a comma (e.g. *Anthomyza bellatrix* Roháçek, 1984). When a species or subspecies is transferred to a genus other than that in which it was first classified, the original authority, including the date, is placed in parentheses.

Adjectives and nouns derived from genus names become Roman with a lower case initial (e.g. *Felis*→feline, *Libellula*→libellulids, *Streptococcus*→streptococcal infection).Those derived from higher taxonomic groups also begin with a lower case letter and are presented in Roman (e.g. Ostracoda→ostracods, Cactaceae→cacti).

A scientific name given at its first mention after a vernacular name should be separated from it by a comma if the two names are exact synonyms (e.g.….the two-spotted cricket, *Gryllus bimaculatus*,…), but not if the vernacular name may apply to more than one species (e.g. the starfish *Asterina pectinifera*, the medaka *Oryzias latipes*).

Abbreviations should be used sparingly but consistently. No full stops are placed after abbreviations ending with the last letter of the full word, after units of measure, after compass directions, after countries and after well-known institutions.

FIGURES AND TABLES

The word Figure should be written out in full and should begin with a capital F, in both the text and captions.

Figures (original or electronic submissions):

- Figures should be planned to fit, after reduction, into a width of either 80, 118 or 165 mm, with a maximum vertical length of 230 mm. Allow space for the caption in the case of figures that will occupy a whole page.
- Graphics, i.e. drawings, graphs or photographs, should be submitted as separate files. Low resolution copies of the figures should be included in the manuscript for review purposes.
- If extensive changes to image files are proposed by the editor, the author will be contacted and the specific image file will have to be re-submitted after the indicated corrections have been implemented.
- Scale bars or scale lines should be used on figures where relevant.
- Captions should not be added as part of the figure file. Number captions clearly and correctly and include either in the main text close to where the figure should be inserted or as a list of captions at the end of the text; not as a separate document.
- Authors wishing to use illustrations already published elsewhere must obtain written permission before submitting the manuscript and provide this to the editor at the time of submission, along with appropriate acknowledgements.
- Do not resample low resolution images to a higher resolution.
- Mosaics should be submitted as separate photographs as TIF/JPG files at 600 dpi or higher. A mockup of the layout should also be submitted. Final layout of the mosaic will be done by our graphics department. Do not number the original images, but do include a scale bar. Indicate the lettering on the mockup and not on the original photographs.
- Manuscripts for which the figures, including line drawings, photographs, graphs and histograms, and maps, do not comply will be rejected for design and layout, even though the paper was accepted for publication, until such time that the authors can provide suitable images. This can significantly delay publication.

Line drawings:

- The original artwork should be in jet-black Indian ink, on fine art paper, 200 gsm. Lines should be clear enough to accommodate reduction. Do not use draughtman's film.
- Drawings in pencil will not be accepted.
- Provide original drawings electronically as bitmap TIF files, 1200 dpi.
- At the request of the author, the Graphic Design Section of SANBI will assist with the scanning of original material. Authors wishing to have the originals of figures returned must inform the editor in writing and mark each original 'To be returned to author'.

Photographs:

- Provide photographs electronically as either TIF or JPG files, 600 dpi or higher.

Graphs and histograms:

- The typeface for all graphs and histograms is Arial.
- Provide graphics originated in CorelDraw (version 16 or lower), as a .CDR file.
- Graphs and histograms generated in MS EXCEL or MS Word, should be provided as is. File conversion into the correct format will be accommodated by SANBI Graphics.
- Images generated in other programmes should be submitted as TIF or JPG files at a resolution of 600 dpi or as encapsulated postscript files (.EPS). If graphs and histograms are submitted in colour, please ensure that the shading used is easily discernible once the file is converted to grayscale.

Maps:

- It is strongly recommended that taxonomic articles include dot maps as figures to show the distribution of taxa. If maps will be reduced to column width (80 mm), the symbols and numbers used must be large enough to accommodate the reduction. The maps should show: numbered grid lines of latitude and longitude; the provinces of South Africa; and a scale line. Maps of neighbouring countries should be treated in the same way, with bordering states clearly labelled. For orientation purposes, a small inset map should appear in a corner of the figure.
- Submit maps electronically as either TIF or JPG files, 600 dpi or higher.
- ArcView GIS maps are acceptable. The layout representing all the appropriate themes (including grid lines) should be submitted as an encapsulated postscript file (.EPS).
- If maps are submitted in colour, please ensure that the shading used is easily discernible once the file converted to grayscale.

Tables:

- Tables should be drawn up in MS Word and not copied and pasted from other software such as MS Excel.
- Avoid copying and pasting text into the table as this often result in nested tables that are problematic to format and edit. Type in all text from scratch.

- Do not submit tables as text with separators such as tabs or commas, submit as MS Word standard tables.
- Do not include text boxes in table cells, type text directly in the primary table cell.
- Use Times New Roman 12pt if possible. However, should the width of the columns and the amount of text make this difficult, the size of the font may be reduced to no less than 9pt.
- If possible, present tables in portrait format. However, if tables must be presented in landscape format, use section breaks before and after the tables to separate it from the main text.
- Do not stretch the table to beyond the size of the paper on screen.
- Use the background fill function to shade cells if necessary. Do not use text highlights.

STRUCTURE OF YOUR ARTICLE

Page 1:

The format of the compulsory cover letter forms part of your submission and is on the first page of your manuscript and should always be presented in English. You should provide all of the following elements:

- **Article title:** Provide a short title of 50 characters or less.
- **Full author details:** Provide title(s), full name(s), position(s), affiliation(s) and contact details (postal address, email, telephone and cellular number) of each author.
- **Corresponding author:** Identify to whom all correspondence should be addressed to.
- **Authors' contributions:** Briefly summarise the nature of the contribution made by each of the authors listed.
- **Summary:** Lastly, include a list containing the number of words, pages, tables, figures and/or other supplementary material with the submission.

Page 2 and onwards:

Title: The article's full title should contain a maximum of 95 characters (including spaces).

Abstract: The abstract, written in English, should be no longer than 250 words and must be written in the past tense. The abstract should give a succinct account of the background, objectives, methods, results and significance of the findings/conclusion

Do not cite references in the abstract and do not use abbreviations excessively in the abstract.

The following points serve as a guide for presenting your manuscript in a well-structure format:

Introduction: The introduction contains two subsections, namely the background section and the literature review.

- **Background:** This section should be written from the point of view of the readers, including those without specialist knowledge in that area and must clearly state and illustrate the introduction to the research and its aims in the context of previous work bearing directly on the subject. The Background section to the article normally contains the following five elements:
  - **Key focus:** A thought-provoking introductory statement on the broad theme or topic of the research.
  - **Context:** Provide the context to the study, which can include the conceptual framework or explain the role of other relevant key variables in this study.
  - **Trends:** Cite the most important published studies previously conducted on this topic or that have any relevance to this study (provide a high-level synopsis of the research literature on this topic).
  - **Objectives:** Indicate the most important controversies, gaps and inconsistencies in the literature that will be addressed by this study. In view of the above trends, state the core research problem and specific objectives that will be addressed in this study.
  - **Contribution to field:** Explanation of the study's academic (theoretical and methodological) or practical merit and its importance (provide the value-add or rationale for the study).
- **Literature review:** The literature review is the second subsection under the Introduction and provides a brief and concise overview of the literature under a separate second-level heading, e.g. literature review. A synthesis and critical evaluation of the literature (not a compilation of citations and references) should at least include or address the following elements (ensure these are in the literature review):
  - Definitions of all key concepts.
  - A critical review and summary of previous research findings (theories, models, frameworks, etc.) on the topic.
  - A clear indication of the gap in the literature and for the need to address this void.
  - A clearly established link that exists between formulated objectives and theoretical support from the relevant literature.

Research method and design (first-level heading):

The methods should include:

- **Materials (second-level heading):** Describe the type of organism/s or material/s involved in the study.
- **Study site (second-level heading):** Describe the site and setting where your study was conducted.
- **Design (second-level heading):** Describe your experimental design clearly. Note: Additional details can be placed in the online supplementary location.
- **Procedure or Methods (second-level heading):** Describe the protocol for your study in sufficient detail (with a clear description of all interventions and comparisons) so that other scientists could repeat your work to verify your findings.

- **Analysis (second-level heading):** Describe how the data were summarised and analysed. Additional details can be placed with the online supplementary information. Do not include lists here as they will be published as supplementary material.

Ethical considerations (first level heading):

- **Ethical clearance (second-level heading):** Articles based on the involvement of animals and/or humans must have been conducted in accordance with relevant national and international guidelines. Approval must have been obtained for all protocols from the author's institutional or other relevant ethics committee and the institution's name and any ethics certificate number/s should be provided at submission.
- **Risks or negative impacts associated with research and mitigation (second-level heading):** This section should consider any risks or negative impacts to the subjects caused by the project (the subject may be a human individual or a population of plants or animals). What precautions were taken to minimise any negative impacts of the research on the subject/s?
- **Permitting (second-level heading):** Projects that required permits for collection, transport or provision of material must provide all relevant permit details.
- **Recruitment and informed consent (second-level heading):** In the case where human subjects were involved, how were subjects recruited? Was there any sense in subjects being obliged to participate or were volunteers recruited. Authors must include how informed consent was handled in the study.
- **Data protection (second-level heading):** Authors must include, in detail, the way in which data protection was handled.

Results (first-level heading):

Results should be presented as follows:

- Present the results of your experiment(s) or research data in a sequence that will logically support (or provide evidence against) the hypothesis, or answer the questions / address the objectives, as stated in the introduction.
- Present the body of the results section in text with the key findings that include references to each of the tables and figures. Report statistical test summaries (test name, p-value) parenthetically (that is, inserted as a parenthesis in brackets) together with the biological results they support. Use the SI unit.
- All units should conform to the SI convention and be abbreviated accordingly. Metric units and their international symbols are used throughout, as is the decimal point (not the decimal comma).

Discussion (first-level heading):

This section normally contains the following four elements. It is suggested that subheadings are used in this section:

- **Outline of the results (second-level heading):** Restate the main objective of the study and reaffirm the importance of the study by restating its main contributions; summarise the results in relation to each stated research objective or research hypothesis; link the findings back to the literature and to the results reported by other researchers; provide explanations for unexpected results.
- **Practical implications (second-level heading):** Reaffirm the importance of the study by restating its main contributions and provide the implications for the practical implementation your research.
- **Limitations of the study (second-level heading):** Point out the possible limitations of the study and provide suggestions for future research.
- **Recommendations (second-level heading):** Provide the recommendations emerging out of the current research.

Conclusion (first-level heading):

This should state clearly the main conclusions of the research and give a clear explanation of their importance and relevance, with a recommendation for future research (implications for practice). Provide a brief conclusion that restates the objectives, the research design and the results with their meaning.

Acknowledgements (first-level heading):

If, through your study, you received any significant help in conceiving, designing or carrying out the work, or received materials from someone who did you a favour by supplying them, you must acknowledge their assistance and the service or material provided. *Authors should always acknowledge outside reviewers of their drafts and any sources of funding that supported the research.*

- **Competing interests (second-level heading):** A competing interest exists when your interpretation of data or presentation of information may be influenced by your personal or financial relationship with other people or organisations that can potentially prevent you from executing and publishing unbiased research. Authors should disclose any financial competing interests, but also any non-financial competing interests that may cause them embarrassment were they to become public after the publication of the manuscript.

  > *Where an author gives no competing interests, the listing will read:*
  >
  > 'The authors declare that they have no financial or personal relationship(s) that may have inappropriately influenced them in writing this article.'

- **Authors' contributions (second-level heading):** This section is necessary to give appropriate credit to each author, and to the authors' applicable institution/s. The individual contributions of authors should be specified with their affiliation at the time of the study and completion of the work. An 'author' is generally considered to be someone who has made substantive intellectual contributions to a published study. Contributions made by each of the authors listed, can follow the example below (please note the use of author initials):

> J.K. (University of Pretoria) was the project leader, L.M.N. (University of KwaZulu-Natal) and A.B. (Stellenbosch University) were responsible for experimental and project design. L.M.N. performed most of the experiments. P.R. (Cape Peninsula University of Technology) made conceptual contributions and S.T. (University of Cape Town), U.V. (University of Cape Town) and C.D. (University of Cape Town) performed some of the experiments. S.M. (Cape Peninsula University of Technology) and V.C. (Cape Peninsula University of Technology) prepared the samples and calculations were performed by C.S. (Cape Peninsula University of Technology).

References (first-level heading):

Begin the reference list on a separate page with no more than 60 references for full length articles and 30 references for short notes. The *Bothalia – African Biodiversity & Conservation* Journal uses the **Harvard referencing style**. Note: no other style will be permitted.

If you use any reference editor to add citations in the text, remove all data fields and replace with normal text before submission.

For journal articles, provide DOIs for as many as possible (usually all papers published in or after 2000). The DOI reference can be provided after a comma at the end of each reference.

TAXONOMIC PUBLICATIONS

Bothalia – African Biodiversity & Conservation publishes taxonomic findings where these align with the scope and focus of the journal (see Scope and Focus of *Bothalia – African Biodiversity & Conservation*). For such works the following headings should be used:

The Abstract and Introduction must follow the guidelines for full length articles, as described above.

Research method and materials (first-level heading):

- **Materials (second-level heading):** Briefly explain from which institutions material was studied, and whether any fresh material was collected as part of the study. If field collecting did take place explain where this was carried out, over what time period and how samples were collected.
- **Procedure (second-level heading):** Explain how observations, measurements and illustrations were done, and what equipment was used.

Taxonomic treatments (first-level heading):

This section serves as a guide to understand and standardise the presentation of taxonomy in research articles and short communications.

More details of rules that must be adhered to can be obtained from:

- The International Plant Names Index at http://www.ipni.org/
- International Association for Plant Taxonomy at http://www.iapt-taxon.org/
- The International Commission for Zoological Nomenclature (http://www.iczn.org)

The following sequence and format must be followed for taxonomic treatments in *Bothalia – African Biodiversity & Conservation*:

Species treatments:

- Basionym (the first name validly published, which has priority over other names later given to the same species): **Name** (bold, not italicised), *author citation* (italicised), author/s of paper in which basionym stated (if different from original author, not italicised).
- Name of the journal/publication written out in full (not italicised), volume: page number/range (date of publication), fig/s.
- Type locality: COUNTRY (upper case), as provided in the original description. Type specimen/s: date of collection, *collector (italicised), collector number* (italicised) (where available), institution code (using global acronym), catalogue number (where available), status (holotype, isotype/syntype, lectotype). If specimen was examined, this is indicated by a '!' after the specimen status.
- Additional references, in chronological order, with author: page (year of publication), figure number/s reflected (e.g. Boris et al.: 14 (1966); Boris: 89 (1967), fig. 9.).
- List of synonyms in chronological order, arranged in groups of nomenclatural synonyms (i.e. homotypic synonyms (based on the same type), followed by heterotypic synonyms (based on a different type), arranged chronologically), with references cited as author, page (year of publication), and figure number/s listed in chronological order.
- Identification of illegitimate names in the nomenclatural component must be accompanied by an appropriate indication of the reason for their illegitimacy. The type details for each heterotypic synonym should be included (institution code followed by catalogue number where available and type status), and those specimens examined by the author/s

must be indicated by an exclamation mark. The full reference for citations must be included in the Reference List.

Examples:

1. **Eremiolirion amboense** (*Schinz*) *J.C.Manning & C.A.Mannheimer* in Bothalia 35: 117 (2005), fig. 4. Type: South West Africa [NAMIBIA], Amboland [**Ovamboland**], Ongangua [Ondongwa], without date, *Ruatanen 344* (Z.holo!).

2. **Walleria gracilis** (*Salisb.*) *S.Carter* in Kew Bulletin 16: 189 (1962). *Androsyne gracilis* Salsb.: 61 (1866). Type: SOUTH AFRICA, **Western Cape**, *William Marsden* [BM, holo!; drawing in Salisbury mss.8: 818 (BM)].

   W. armata Scltr. & K.Krause in Krause: 235 (1921). Type: SOUTH AFRICA, [**Western Cape**, near Klawer], [Farm] Windhoek, 8 July 1896, *R. Schlechter 8074* (B, holo [not seen]; BM!, BR!, COI!, GRA!, K, MO!, PRE!, S!. iso).

3. **Plagiotaphrus improvisus** *(Attems 1934) Hoffman* in Revue de Zoologie et de Botanique Africaines, 83 (3–4): 209 (1971), fig. 2. *Megaskamma improvisa:* Attems: 16: 13 (1934), figs 14–17. Type: **ANGOLA**, near Cuanza River, Biėi District, Jan. 1932, *F. Haas* (SMF 1694, holo. [not seen] 1 male).

- Lectotypes or neotypes should be chosen for correct names without a holotype. It is not necessary to lectotypify synonyms. When a lectotype or neotype is newly chosen, this should be indicated by using the phrase “here designated”. If reference is made to a previously selected lectotype or neotype, the name of the designating author and the literature reference should be given. In cases where no type was cited, and none has subsequently been nominated, this may be stated as “not designated”.

Description of new taxa:

- All newly described taxa and newly proposed synonyms and new combinations should be explicitly designated as such, e.g. fam. nov., trib. nov., gen. nov., sp. nov., nom. nudem., syn. nov., comb. nov.

Name (bold, not italicised) sp. nov. authority (if different to the authors of the manuscript)

TYPE/S: (holotype followed by paratype/s) (COUNTRY (upper case), **province** (bold), locality as given by original collector (if in foreign language or using archaic or outdated place names then these must be placed in inverted commas, with modern equivalent of collecting locality in square brackets (if relevant)), geographic co-ordinates (if the geographic co-ordinates were not provided on the specimen label or provided by the collector, and were identified by the author using a gazetteer or Google Earth, this must be indicated by including the co-ordinates in square brackets, altitude, habitat or other available, relevant collecting details, date of collection, *collector’s name (italicised), collector’s number (italicised*) (if available), (institution where specimen is housed (using global acronyms for these), catalogue number (if available), number of specimens by male and female (where relevant)).

Examples

1. **Lasiosiphon rigidus** J.C.Manning & Boatwr., sp. nov.

   TYPES: SOUTH AFRICA, **Northern Cape**, Tankwa [Tangua] Karoo National Park, SW foot of Leeuberg, along drainage lines, [32°18,2’S / 20°0.3’E, 414 masl], 20 Jun. 2012, *Manning 3363* (NBG, holo., MO, PRE, iso).

2. **Doratogonus microsetus** sp. nov.

   TYPES: SOUTH AFRICA, **Mpumalanga**: Wakkerstroom, 27.36670°S / 30.01670° E, 20 Dec, 2000, *D. Forbes (*NMSA 21786, 1 male holo.; NMSA 21787, 2 males, 1 females, para.).

Second-level headings for taxonomic treatments:

- Description (with third-level headings if required, and according to diagnostic characters for the particular taxon)
- Distribution and habitat
- Ecology
- Etymology
- Local name/s
- Uses / economic value
- Diagnosis and relationships
- Conservation status – comment on whether included in existing Red Lists, or whether the species would potentially qualify as threatened and describe current and potential threats.
- Other material examined (country (upper case), province (bold): locality as given by original collector, modern equivalent of collecting locality in square

brackets (if relevant), co-ordinates (degrees, minutes decimal) (in square brackets if gazetteer or Google Earth used by author), approximate altitude, date of collection, *collector's name (italics), collector's number* (italics) (if available) (institution where specimen is housed (using international acronym or code for these), catalogue number (if available), number of specimens by male and female (where relevant)).

- List of specimens must be arranged alphabetically by country, and within countries, by province in alphabetical order, and within provinces, alphabetically by locality name, and as far as possible keeping those specimens from the same locality together, then in chronological order by collection date.
- Herbarium acronyms follow Index Herbariorum [Thiers, B. [continuously updated]. Index Herbariorum: A global directory of public herbaria and associated staff. New York Botanical Garden's Virtual Herbarium. http://sweetgum.nybg.org/ih/]. The accepted acronyms for other institutions can be obtained from the Global Registry of Biorepositories (GRBio) (http://grbio.org).
- Original locality information in a foreign language or using archaic/outdated place names should be indicated using inverted comas, with any relevant corrections for modern usage, including conversions to metric units, added in square brackets.

The date of collection is to be presented as day, month of the year (abbreviated as Jan., Feb., Mar., Apr., May, Jun., Jul., Aug., Sept., Oct., Nov., Dec.), and year in full.

Geographic co-ordinates must be presented as taken from a GPS, or from an online gazetteer or georeferencer in degrees, decimal minutes (DDM). Records must also indicate the hemisphere (E or W and N or S, and the estimated/approximate altitude. If the geographic co-ordinates and approximate altitude were not provided on the specimen label or provided by the collector, and were identified by the author, this must be indicated by including the co-ordinates in square brackets.

For species that may be threatened by over-collecting, the co-ordinates can be degraded to reflect only the degrees and minutes. In the case of old specimens where the exact locality is unknown the degree and minutes or equivalent, or the degree or quarter degree grid square can be provided.

Examples:

1. SOUTH AFRICA. **Western Cape**: Near Eendekuil, western foot of Piekenierskloof Pass, [32°37.136'S / 18°57.525'E 476masl], 28 Aug. 2009, *Magee, Boatwright, Manning and Goldblatt 161* (NBG, PRE, K, BOL); roadside near Gouda, [33°37.136'S / 19°2.044'E, 85masl], 09 Sept. 1951, *Esterhuysen 18840* (BOL [3 sheets], K, PRE).Tulbagh, 33°17.126'S / 19°8.257"E, 162masl, Sept. 1919, *Bolus 16734* (BOL);
2. SOUTH AFRICA: **KwaZulu-Natal:** Nkandhla Forest, in forest along dirt road, 28º43'38.592"S / 31º07'58.281"E, 1121 masl, 19 Nov, 2001, *A. Armstrong & H. Murray* (NMSA 21970 [1 male, 1 female]).

Language for these sections must be as concise as possible, using principles instead of verbs.

The remaining first-level headings (Discussion, Conclusions, Acknowledgements, Competing interests, Authors' contributions and References) must follow the same format as for full length articles, as detailed above.

Images – low resolution version in the text file; high resolution files – correctly labelled – as separate JPG, TIF or EPS files.

Identification keys: Dichotomous keys must use sequential numbering, with the two parts of the couplet numbered 1a, b; 2a, b etc. New species included in keys must be bolded and not italicised, and sp. nov. must be stated, while other species names must not be bolded, must be italicised, and must include the species authority in the correct format.

Illustrations for taxonomic works: Descriptions of new plant species should include a photograph of the holotype specimen, unless there is a good reason for not providing this. For all taxa, descriptions of new species and taxonomic revisions should include annotated illustrations that clearly show and indicate diagnostic characters.

Nomenclatural changes

Bothalia – African Biodiversity & Conservation will accept notes on nomenclatural changes. Authors are encouraged to include all name changes into a single manuscript and not to split these into separate manuscripts. Note that where a nomenclatural changes are a formality, and not based on research findings presented, the manuscript may not be subjected to a full review process. In such cases the publication will clearly state that the paper has not been peer reviewed.

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